A Ship Emission Estimation Methodology with Spatial Mapping Capability for Assessing Regulation Effectiveness

by

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Abstract

In response to global warming, the International Maritime Organization (IMO) set rules of 50% Greenhouse Gas (GHG) reduction by 2050, from 2008 levels. Signatory countries to the IMO's regulation require frequent assessment of the contribution of GHG emissions from shipping calling at their ports or trading in their territorial waters to ensure their compliance with the regulations. This demands a rapid and accurate method to assess shipping's contribution to GHG emissions.

Current methodologies for estimating emissions from ships can be described on a scale between bottom-up and top-down methods. Top-down methods provide rapid estimates – primarily based on fuel sales reports - without considering individual vessel details. Therefore, they are less accurate and do not provide a breakdown of emissions by ship types or in specific regions. Bottom-up methodologies are detailed vessel-based estimates; however, they are data and time-demanding.

The novel Ship Emissions Assessment method (SEA) fills the gap between bottom-up and top-down methods by providing an innovative hybrid solution for rapid but accurate ship emission estimation. It uses publically available, cost-effective data sets previously unused for emission estimates.

The SEA method was demonstrated for containership traffic in 2019 for three ports: Trieste, Rijeka and Venice. The CO_2, SO_x and NO_x emissions were quantified per transported container (TEU).

The SEA method requires from 1/500 to 1/50 of the data used by the equivalent bottom-up calculations, relying on AIS signals in a temporal resolution ranging from minutes to an hour. Consequentially, it requires 1/100 to 1/10 of the bottom-up processing time, providing results comparable to the detailed bottom-up methodology.

This Thesis also explores the value of presenting emissions spatially on a ship density map with the example of CO_2 production presented. The SEA method provides a simple and inexpensive tool for assessing emissions from ships and generates data for emissions per unit of cargo.

Dedicated to my sons, Stipan and Lovro, who are my inspiration.

The time we spend at sea, loving and protecting it,
the life it withholds and the energy it returns to us,
is the time worth living on this beautiful blue planet.

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I would like to thank my parents for bringing up the free spirit in me by teaching me to live in balance with the unspoiled wilderness of the Adriatic Sea. I am grateful for the years we had in our summer retreat in Istria, for our unique rocky cove and secret paths through the forest that led to it, for the little yacht they let me use and navigate to explore Croatian islands, for letting me have my skipper licence when I was 14 years old and for teaching me to swim in open waters, dive and snorkel before I was three years old.

During my lifetime, we noticed a rapid drop in the number of fish and species diversity. My free spirit and curiosity led me to undertake this research, which started as a personal, emotional and intellectual journey through which I have unexpectedly discovered an entirely new part of myself, a scientist.

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Author's Declaration

I have read and understood the rules on cheating, plagiarism, and appropriate referencing as outlined in the ethics handbook, and I declare that the work contained in this thesis is my own unless otherwise acknowledged. I wish to further declare that some parts of this thesis may contain relevant texts and/or data from my published and unpublished works, which were either quoted verbatim or further analysed to new revealing depths.

Signed:

Tamara Topić

List of Publications Resulting from this Research

Topić, T., Murphy, A.J., Pazouki, K. & Norman, R. (2020) ***Assessment of Ship Emissions and Estimation of the Effectiveness of NOx Emissions Control Area (NECA) Scenario for Ports in the North Adriatic Sea.***

Sustainable Development of Energy, Water and Environment Systems (SDEWES), Paphos 2022.

Topic, T., Murphy, A.J., Pazouki, K. & Norman, R. (2021) ***Assessment of ship emissions in coastal waters using spatial projections of ship tracks, ship voyage and engine specification data.***

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Topić, T., Murphy, A.J., Pazouki, K. & Norman, R. (2020) ***Assessment of Ship Emissions in Coastal Waters using Spatial Projections of Ship Moves (Ship Density) and Port Congestion Data.***

2nd Latin American SDEWES Conference, Buenos Aires 2020.

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ACRONYMS

AIS	Automatic Identification System
BC	Black Carbon
EEOI	Energy Efficiency Operational indicator
EF	Emission Factor
EFs	Emission Factors
GEF	Global Environment Facility
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HSD	High Speed Diesel
IMO	International Maritime Organisation
LF	Load Factor
LNG	Liquified Natural Gas
MGO	Marine Gas Oil
MSD	Medium Speed Diesel
NECA	NOx Emission Control Area
NOx	Nitrogen Oxides
PEMS	Portable Emission Measurement System
PM	Particulate Matter
RPM	Revolutions per Minute
SDGs	Sustainable Development Goals
SEA method	Ship Emission Assessment methodology
SECA	Sulphur Emission Controlled Area
SECAs	Sulphur Emission Controlled Areas
SEEMP	Ship Energy Efficiency Management Plan
SOx	Sulphur Oxides

SSD	Slow Speed Diesel
STEAM	Ship Traffic Emission Assessment Model
TREAD	Traffic Route Extraction and Anomaly Detection
ULSHFO	Ultra-Low Sulphur Heavy Fuel Oil
UNFCCC	United Nations Framework Convention on Climate Change
VLSMGO	Very Low Sulphur Marine Gas Oil
VOC	Volatile Organic Compounds
YOB	Year of Built

Chapter 1. Introduction to Thesis

1.1 Introduction to Chapter 1

This thesis proposes a novel methodology for estimating quantities of ship exhaust emissions that impact air quality, participate in the climate change process and contain particulates harmful to human health and the environment. This introductory chapter summarises the background and motivation for the Thesis, the research aims and objectives, and the thesis structure.

Globally, shipping accounts for 80 per cent of goods transported by volume and accounts for three per cent of anthropogenic global greenhouse gasses. Ship exhaust emissions contain nitrogen, oxygen, carbon dioxide and water vapour, with smaller quantities of carbon monoxide, sulphur and nitrogen oxides, partially reacted and non-combusted hydrocarbons and particulate matter (Woodyard, 2004; AIRUSE LIFE 11 ENV/ES/584, 2016). Primarily of concern are greenhouse gases responsible for global warming and toxic, noxious and sulphuric gases, a threat to health and the environment.

Ships generated greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), accounted as carbon dioxide equivalent (CO_2e), equated to 1,076 million tonnes of CO_2e in 2018 (Faber et al., 2020). International Maritime Organisation (IMO) reported an increase of 2.89% in shipping emissions share in global anthropogenic emissions in 2018, which is a consequence of an increase in shipping fuel consumption trends explained by an increase in shipping activity, ship number and size. The total yearly amount of global ship GHG emissions could be compared to the total yearly GHG emissions of countries to understand the scale of the problem better. If global shipping GHG emissions were classed as emissions of a country, shipping would be sixth in the list of highest CO_2e emitting countries globally (Bullock et al., 2020).

Ships generated toxic gases, nitrogen and sulphur oxides NO_X and SO_X, present a hazard for human health due to their capacity to form particulate matter $PM_{2.5}$ in secondary reactions after the combustion. Additionally, nitrogen and sulphur oxides threaten the environment by causing eutrophication, acidification of the seas and waters, and ground-level ozone formation (Andersson et al., 2016). The Fourth IMO GHG Study (2020) reported emissions from global shipping to produce 18.6 million and 10.6 million tonnes of NOx and SOx, respectively, which accounted for 15% and 13% of all NO_X and SOx produced from anthropogenic sources. This percentage is particularly concerning because ship emissions are generated in concentrated amounts in localised geographical areas, during ships' transit, berth and anchor, where sulphurous and noxious emissions impact human health and coastal ecosystems (Department for Transport, 2019a; Department for Transport, 2019b)

Ships tend to spend anywhere from several hours to several days in ports using engines for manoeuvring, hoteling and port operations - generating alarming levels of toxic SO_X and NO_X emissions in the vicinity of densely populated port cities and coastal areas.

However, ship emissions tend to get overlooked by regional emission inventories, as shipping transit tends to fall outside the boundary of local authorities’ areas of concern, particularly if ships are transiting or anchoring outside the port jurisdiction area. Countries report yearly GHG emissions following the guidance set by the Intergovernmental Panel on Climate Change (IPCC), as required for submission to the United Nations Framework Convention on Climate Change (UNFCCC). However, under this guidance, shipping GHG emissions are reported but not included in countries' total. Additionally, emissions of toxic gases SO_X and NO_X from international shipping remain unaccounted.

Unaccounted ship airborne emissions of SO_X and NO_X can, in turn, exceed allowed concentrations of emissions - presenting serious risks. Toxic emissions from ships can accumulate in severe concentrations or hot- spots (Vicente-Cera et al., 2020; Tichavska & Tovar, 2015), with the capacity to exceed allowed daily and yearly amounts (Alebic-Juretic & Mifka, 1981; Merico et al., 2017, 2016; Ytreberg et al., 2021), posing a severe risk to human health and the environment.

Coastal nations and, particularly, island-based populations are exposed to exhaust emissions of international shipping traffic, which is not considered as a major contributor to local area emissions. This situation needs urgent action, and ship emissions need to be assessed in geographical areas with existing shipping traffic, extending along the shipping tracks regardless of national borders or port and city formal boundaries. A methodology is needed that will enable regular ship emission assessment in ports and designated areas, which will provide sufficient evidence for annual port emission reports and for regional authorities looking to increase emission control measures.

Ship emission quantities are increasing yearly due to an increase in ship number and size, driven by growing trends in international maritime trade and an increase in port capacities. Shipping trade exceeded 10 billion tonnes in 2015, taking 80% of global trade by volume, while transportation by air, road and rail accounts for the remaining 20% (Mangan et al., 2016). The IMO has done extensive research on shipping emission trends which was presented in four IMO GHG Studies. The first IMO GHG Study was published in 2000, the Second in 2009, the Third in 2014 and the current Fourth in 2020. Across the 22 years of the IMO ship emissions study period, the trend in shipping emissions shows a growth tendency related to the expansion in shipping trade demand. Additionally, the percentage of shipping's contribution to global anthropogenic emissions is increasing. For example, in 1996, ships generated 880 million tonnes of CO_2 and contributed 1.8% to global anthropogenic emissions (IMO, 2000), which increased to 885 million tonnes, or 2.8% in 2007 (Smith et al., 2014).

A positive trend can be observed in 2008 when shipping's overall GHG emissions, including CO_2, were reduced due to introducing the EEOI[1] and AER[2] emissions reduction measures (IMO, 2000). However, from 2008 to 2014, the trend in GHG emissions continued with growth related to the increase in the international shipping market demand, offsetting the effectiveness of mitigating measures (Unctad, 2015; Faber et al., 2020). In 2018 ships generated 1,056 million tonnes of CO_2, which is 120% compared to the first assessment in 1996 and 9.3% growth since 2012.

Similar trends in emission growth coupled with expansion in shipping trade demand have been recorded for SO_X and NO_X; however, the effect of emerging mitigating measures has not been assessed enough, to understand the measures effectiveness.

[1] EEOI - Energy Efficiency Operational Indicator is an IMO operational measure which requires that operators measure fuel consumption and improve energy efficiency of the ship in operation. It is based on the Ship Energy Efficiency Management Plan (SEEMP), which is a tool for ship performance recording and optimisation.

[2] AER- is the IMO tool to measure carbon intensity of operating ships, as a product of fuel consumed by a ship and the cargo capacity, divided by the total miles travelled.

Emissions from ship exhausts need to be quantified to understand the magnitude of the problem; however, taking measurements of exhaust emissions on-board all ships in operation is not viable, as it would be expensive in terms of technology, data processing and time, so analysis of emission quantities must be based on estimations. This situation requires a methodology for emission assessment from ships. Emissions from ships need to be estimated regularly to understand potential emission level risks and maintain effective emission reduction measures.

Current methodologies for estimating emissions from ship exhausts vary between top-down and bottom-up estimates. Top-down ship emission estimates are rapid but less accurate in providing specific emission data for local areas or vessel-based emissions. Bottom-up vessel-based emission estimates are accurate but are data and time-intensive and, therefore, a costly process. Bottom-up estimates take a long time to deliver, so they provide results with a time gap of two years or more; for example, the First IMO GHG study was published in 2000, providing results for 1996.

These *top-down* and *bottom-up* approaches, or a combination of the two, depending on the intended purpose, are the most common methods (Jalkanen et al., 2012; Huang et al., 2017; Tichavska & Tovar, 2015; Kågeson, 2005; Nunes et al., 2017; Goldsworthy & Goldsworthy, 2015a, 2019; ED61406- Issue Number 5, 2017; Schim van der Loeff et al., 2018) utilised to collect and process the direct and indirect data precursors of ship emissions. For example, IMO (2014) and (2020) use both top-down and bottom-up approaches to verify estimated amounts and methodologies.

A *top-down* approach is characterised by using highly aggregated information on a relevant shipping activity, e.g. total fuel consumption (or even sales) for a fleet of ships over an extended period of time, relevant to a wide geographical region (Faber et al., 2020; Scarbrough et al., 2017; Olmer et al., 2017). The corresponding emission factors (EFs) are highly aggregated with averaged values and do not consider the specific conditions that led to the instantaneous emission production in any given circumstance. So, although *a top-down* approach is relatively inexpensive (e.g. it requires a small quantity of data), it is of low resolution (in time and space) and unable to accurately reflect emissions in response to specific shipping activities.

A *bottom-up* approach adopted by different authors typically estimates near-instantaneous emission production on a vessel-by-vessel basis at high resolution (in time and space) (Smith et al., 2014, 2020; Goldsworthy, 2017; Jalkanen et al., 2016; Trozzi, 2010; Huang et al., 2020; Toscano et al., 2021).

The EFs used can vary over the range of chosen operating conditions; for example, they could be continuously variable over the full range of engine power output (Campling et al.,2013). Variable EFs approach is data-intensive[3] and consequently relatively expensive; it can accurately reflect variations in emission production at high resolution.

Bottom-up, vessel-based methodologies to estimate emissions from ships rely on the Automatic Identification System (AIS) data. Bottom-up methodologies need ship power output data combined with ship speed over ground to estimate the engine load. The accuracy of bottom-up methodologies can be improved by identifying accurate emission factors for each type of ship's main and auxiliary engine and relating them to the activity.

The *bottom-up* vessel-based methodologies provide detailed quantification of emissions for specific areas; however, they use a complex and time-consuming process which delays the publication of data and is therefore not practical for rapid assessment or providing current data for improvements of regulations (Goldsworthy & Goldsworthy, 2015b, Huang et al., 2017). Time is required to generate historic datasets achieved by recording real-time AIS data, followed by complex data computations calculating ship movement trajectories, which are then applied to activity-based emissions estimations. To bridge some of this complexity, a *bottom-up* Vessel-based assessment Peng et al (2020) uses a sampling technique where a certain number of ships represent emission quantity contributions for different types and sizes of ships. This bottom-up ship exhaust emission estimation method intends to assess geographic areas using average emission factors to estimate NO_X quantities. Although this method is vessel-based, it does not provide an accurate understanding of the impact of ship technical abatement measures on overall emissions, which is explained further in Chapter 5, Figure 5.7.

[3] Data intensive – needs high temporal resolution of AIS data, which requires acquisition of expensive historical datasets (explained in Chapter 3, Section 3.2.2); or instantaneous data acquisition from free AIS sources (for example a one-year data set will require one full year to obtain).

The third and fourth International Maritime Organisation (IMO) Greenhouse Gas (GHG) studies (2014, 2020) are detailed *bottom-up*, high budget studies that provide global statistics and emission factor standards. The IMO GHG studies provide detailed results for the emissions from shipping at the global scale; hence, to replicate that study for a specific region, the IMO approach requires extensive time and effort. Therefore, the Ship Emissions Assessment methodology (SEA), developed in this Thesis, would provide a time and data-efficient assessment of ship emissions in geographical areas.

The novel SEA method is proposed as an innovative hybrid solution to bridge the gap between the top-down and bottom-up methodologies for ship exhaust emission estimation. The SEA methodology utilises elements of the bottom-up and top-down methods to achieve data and time efficiency, which will enable the method to be used regularly by stakeholders needing accurate indications of emissions in ports and broad geographic areas. This will allow the effectiveness of potential emission control measures to be predicted prior to being adopted.

The SEA methodology is presented in Chapter 4, in its entirety, it is validated in Chapter 5, and its application is demonstrated in Chapter 6.

The SEA method is novel in that it replaces the use of AIS vessel-based raw data with rapid analysis of publically available ship track density data and average voyage information, as presented in Chapters 4 and 6. It combines average voyage distance with average voyage speed to estimate ship activity for emission assessments - saving cost by reducing data acquisition and processing time, especially when many ships need to be analysed simultaneously, like in the case of geographical area assessments.

The SEA method was applied to assess containerships from geographically diverse ports. Containerships were proven to be the highest polluting vessels according to IMO statistics (2014, 2020), which was the reason for this choice of ship type. Three ports with different ship traffic organisation and geographic features were chosen to demonstrate the SEA method and how it adapts to different processes for entering and exiting the port. Subsequently, the SEA method’s ability to estimate historical emissions for the preceding 12 months was demonstrated and is presented in Chapter 6.

This testing was necessary to understand the applicability of the SEA method. Results were validated using a comparison of methods because verification against empirical data was not possible due to limited data available from emission measurements on board ships. Therefore, the SEA method's level of precision was verified by comparing it against results from the existing bottom-up IMO method.

The motivation for this PhD work was to enhance the understanding of ship emissions by developing an improved and simple to use yet accurate assessment method, with results that compare well to bottom-up methodologies and can subsequently assist policymakers in delivering optimal ship emissions reduction measures.

1.2 Aim and Objectives

1.2.1 Research Aim

To develop a method to assess the levels of emissions from ships in designated geographic areas, using ports as central hubs to assess the effect of emission reduction measures (technical and policy).

The methodology will encompass diverse changes in regulations and technology and provide a tool for generating a spatial map of ship emissions for any port or geographic location.

The methodology will use publically available resources that can be accessed by any stakeholder globally.

1.2.2 Research Objectives and How Objectives Were Met

The following objectives were defined to address the aim of the research:

1) Conduct research to understand to what extent shipping contributes to airborne pollution in regional seas, specifically in coastal port-city areas. (Chapter 2)
2) Investigate technical and policy measures for reducing air pollution from ships in coastal waters. (Chapter 2)

3) Investigate ship activities and power demand within the geographic area around the port, using the *bottom-up* model. Use the bottom-up model to estimate ship emissions for individual containerships within the port boundaries. (Chapter 3)
4) Develop the Ship Emissions Assessment methodology – SEA - according to the research aim. Use the SEA methodology to explore previously unused datasets that could reduce methodology data requirements. (Chapter 4)
5) Validate the SEA methodology results by comparing them to the bottom-up model (implemented in ***objective three,*** Chapter 3). (Chapter 5)
6) Apply the SEA methodology to estimate emissions from ships in different ports. Use the SEA methodology to compare emission regulation effectiveness in selected ports. Suggest emissions reduction measures and present possible savings in emissions for different regulatory measures. (Chapter 6)
7) Demonstrate application of the SEA method to present CO_2 emissions from ships spatially. (Chapter 4)

Objective One is explained in the Introduction of Chapter 1 and Sections 2.1 and 2.2. of the Literature review, Chapter 2. The analyses of existing measures (technical and policy) were conducted in the scope of ***Objective Two*** and presented in Chapter2.

The *Bottom-up* AIS model was developed in the scope of ***Objective Three*** to analyse ship activity within port boundaries. The *Bottom-up* AIS methodology, based on interpretation of the 3rd GHG study by IMO (2014), is considered the closest reference to ship emission measurements accessible through publically available sources (Chapter 3).

Objective Four was to develop the main method according to the research aim and research question (Chapter 2, Section 2.4). The SEA methodology is presented in Chapter 4, and its application to different ports is demonstrated in Chapter 6. Spatial presentation of emissions of CO_2 was explored and explained in Chapter 4, Section 4.6.

Objective Five was completed by comparing the novel SEA and the *Bottom-up* AIS method. To validate the estimation of emissions using the SEA method, different data sets were applied with the results compared to those obtained through the *Bottom-up* AIS methodology, which is presented in the validation, in Chapter 5.

Validation was not a single process; it was phased throughout the research, from the novel method design phase to the confirmation of final results. To validate the SEA method using comparative analysis, it needed to be applied to the same dataset as that referenced in the *Bottom-up* AIS method.

Detailed validation of the SEA method model was conducted in comparison with the *Bottom-up* AIS mode for fleets of containerships over the course of one year. This validation helped establish the best choice of parameters out of datasets which are publically available and which could be used as a proxy for values needed in emission estimates, to bridge the need for massive AIS datasets. Data acquisition and previously unused datasets are explained in Section 4.5.

Objective Six was completed by application of the SEA method in three ports in the north Adriatic Sea, Port of Trieste, Port of Rijeka and Port of Venice. Emissions from ships were quantified for CO_2, SO_X and NO_X pollutants. Emissions regulation effectiveness in selected ports was compared by comparison of grams of pollutants emitted per volume of transported cargo in TEU (g/TEU). The port with the highest pollution per volume of cargo was used as an example to forecast scenarios of different regulatory measures, and possible savings in emissions were presented.

Objective Seven was demonstrated in Chapter 4 for the Port of Trieste. Emissions of CO_2 were presented in a spatial map of historical ship tracks.

1.3 Research question

The literature review presented in Chapter 2 has identified a gap between top-down and bottom-up methodologies for ship exhaust emissions estimation, which do not provide adequate solutions for time-efficient geographic area emission inventories and ship exhaust emission assessments. A more rapid yet accurate analysis of regional ship emissions is needed, which will enable quantification and spatial presentation of emissions, using an estimation methodology to avoid the extensive processing of fuel consumption measurement data. A method is needed which will provide evidence of emissions from ships in coastal areas for decision-making bodies. The methodology should enable the assessment of emissions from a large number of ships in coastal areas and test scenarios for improvement in regulations to present possible savings in emissions if such changes in regulations are applied. The method should enable practicable assessment of activity and emissions of ships in coastal areas, using publically available resources, which can be accessed by all stakeholders. This, in particularly, cancels out the use of measurements on board ships, which are difficult to obtain, data on regional fuel trade quantities and any other restricted data.

The ship emission estimates should be comparable to bottom-up methodology and applicable as a support tool in emissions from ships estimation for regulatory annual port emissions reporting.

This led to the following research question:

How to rapidly estimate emissions from ships in defined geographic areas to enable assessment of regulation effectiveness by using publically available resources?

To analyse ship emissions in different geographic areas, two models were used:

- A bottom-up model, which is presented in Chapter 3, which is an interpretation of the IMO ship emission estimation method.
- The ship emissions assessment (SEA) model, is a hybrid model that fills the gap between the top-down and bottom-up methodologies, as presented in Chapter 4.

The models developed have been used for the following purposes:

- *To accurately estimate emissions for individual vessels and create a dataset for testing and validation of the newly developed, more rapid emission estimates, as presented in Chapter 3.*
- *To assess emissions from ships in defined geographical areas using publicly available resources, quantify emissions of CO_2, SO_X and NO_X and present CO_2 emissions in a spatial map*
- *To understand the effects of ship emission reduction measures (technical and policy), as presented in Chapter 6, Section 6.10.*
- *To estimate ship emissions in different ports with different shipping traffic organisations, as presented in Chapter 6.*

1.4 Thesis Layout

The Thesis layout is structured in seven chapters, as follows:

Chapter 1: Introduction to the Thesis, including the identified challenges and subsequent motivation for the research. The research aims and objectives are presented, along with a brief outline of how the objectives were met.

Chapter 2: Literature Review. This chapter reviews published literature to better understand the key background challenges, which include raising concerns about the impact of ship emissions on the population and the environment, leading towards the need to assess and quantify airborne ship emissions. Top-down and bottom-up ship emission estimation methodologies were reviewed, and the research gap was identified. The literature review highlights the need for a low-cost methodology that will estimate emissions from ships accurately enough to be used to assess regulations for emission abatement.

Chapter 3: This chapter introduces a bottom-up model, which implements the IMO (2014) methodology for vessel-based ship emissions estimation. This bottom-up ship CO_2, SO_X and NO_X emission estimation model uses historical records of AIS signals to analyse vessel position, speed, direction and time of call, combined with ship technical data obtained using publically available portals.

Chapter 4: This chapter introduces the novel ship emissions assessment methodology (SEA), which was developed during the course of this research. The SEA methodology can produce emission inventories for ports and geographical areas as rapidly as top-down methods with an accuracy level comparable to the bottom-up method. To detect ship activity for emission inventories, most methodologies require instantaneous AIS data acquisition or historic ship activity data collected over the course of one year, which makes them time-intensive and data demanding. Other bottom-up methodologies require the use of historic datasets, which are expensive. The SEA method uses datasets up to 500 times reduced in size, which reduces purchasing costs significantly, and enables the assessment of emissions for hundreds of ships using standard personal computer operation capacity.

The SEA methodology is described, which provides an innovative solution for emission assessment, and provides a spatial presentation of where the emissions are occurring.

Chapter 5: The SEA methodology validation is presented in this chapter. Measurement data of the necessary scale are not available in public literature; therefore, the SEA methodology was validated using a comparison of methodologies. The methodology chosen as a reference for validation was a vessel-based, bottom-up method, as described in Chapter 3. Chapter 5 presents a comparison of these results for a case study on containerships.

Chapter 6: Application of The SEA methodology was applied to compare emissions reduction effectiveness for a case study of three ports. The selected ports were chosen in the North of the Adriatic Sea, the ports of Rijeka and Trieste, seaports in natural enclosed bays and the port of Venice, a seaport located within the artificial barrier of the Venetian lagoon. The rationale for the selection of the ports was explained in Section 6.2. This chapter presents the process of data acquisition without the need for time demanding AIS data collection or expensive historical data acquisition by using the existing ship voyage and port operation performance data combined with inexpensive aggregated ship historical track maps to recreate shipping activity and consequentially ship energy demand and emissions. Obtained results are presented quantitatively and compared. Additionally, the SEA method is applied to forecast the effectiveness of improved regulations applied to the highest emitting port.

Chapter 7: In the concluding chapter, the novelty of the proposed SEA methodology is explained, and contributions are highlighted. A research summary is provided in the general conclusions, and recommendations for future work and application of the SEA methodology are suggested.

1.5 Summary of Chapter 1

This chapter has presented the background of the Thesis, followed by the aims, objectives and motivation for the PhD research. Ship emissions present a severe and growing problem, which is why the IMO has introduced stricter global regulations for emission abatement.

The motivation behind this Thesis is to improve the understanding of ship emission technical and geographical sources. This Thesis aims to evaluate the effectiveness of reduction measures by delivering a rapid methodology to assess emissions from ships in ports and coastal areas where concentrated ship emissions could harm people and the environment.

Chapter 2. Literature Review

2.1 Introduction to Chapter 2

The literature review was conducted following the research question defined in Chapter 1, Section 1.2. The research background and concerns about emissions from ships in coastal regions and globally are explained in this chapter. Research of publications in scientific journals, reports from research projects and governmental institutions was conducted to gain an understanding of the impact of ship emissions as the first research objective. The need to quantify ship emissions, particularly in densely populated coastal areas and ports, is evidenced in section 2.2. In this chapter, recent *top-down* and *bottom-up* methodologies for the estimation of ship emissions are reviewed and critiqued, and the research gap is identified.

2.2 The impact of ship emissions

Current IMO regulations expect shipping to reduce GHG emissions by 50% from levels in 2008; however, those regulations are to be revised and strengthened in 2023 to meet the Paris Climate Agreement. Ships trading in the UK will need to meet UK's net-Zero GHG emission target by 2050 (UK Parliament POST, 2022). The action is required to raise awareness of the need to strengthen ship emissions reduction measures globally. This Thesis focuses on developing a tool for emissions from ships assessment, applicable in any global area to quantify emissions and thus raise awareness of the impact of ship emissions, particularly in areas of most significant concern. Areas of substantial concern were identified through a literature review of scientific evidence presented in this Section.

The level of ship exhaust emissions is concerning because a significant part of the total emitted quantities of toxic gases is generated when ships transit close to populated areas and during manoeuvring and hoteling in ports (Trodden et al., 2015; Trodden & Haroutunian, 2018). Marine diesel engines emit carbon dioxide (CO_2), sulphur oxides (SO_x), nitrogen oxides (NO_x), primary and secondary particulate matter (PM) and a range of volatile organic (VOC) and other compounds (AIRUSE LIFE 11 ENV/ES/584, 2016). The impact of CO_2 on the global climate has been well documented in the literature and recognised by global institutions (Wan et al., 2018; EU Commission, 2013; Eyring et al., 2010)

Compounds present in ship exhaust gas emissions, CO_2, NO_x and SO_x, react with the atmosphere and the sea, with different adverse effects. Carbon dioxide dominates the global warming effect due to its long life and presence in the atmosphere (Styhre et al., 2017). Global warming effects are causing climate change, sea-level rise, adverse weather events, loss of biodiversity and climate-induced displacement of millions of people (imo.org, 2018; United Nations, 2018; Jungcurt, 2018; The Clean Shipping Coalition; IMO, 2016)

The contribution to climate change of CO_2 is now well established. Additionally, CO_2 contributes to the rising acidity of the sea, combined with the other contributors found in ship exhaust fumes, sulphur oxides and nitrogen oxides (Turner et al., 2018).

Sulphur and nitrogen oxides are toxic to people and the environment. The danger of the increasing presence of SO_X and NO_X in the atmosphere is in the capacity of those gases to react and participate in the formation of secondary particulate matter ($PM_{2.5}$), which severely affects human health and the environment (EU Commission, 2018; Ballini & Bozzo, 2015; Viana et al., 2020, Apte et al., 2018). The NO_X and SO_X emitted by ships are directly accountable for significant levels of secondary and primary particulate matter consisting of black carbon (BC) and volatile organic compounds (VOC), which are particularly concerning in coastal cities and populated areas (Sofiev et al., 2018; Gilbert et al., 2018, Contini et al., 2021)

Once released into the atmosphere, SO_X and NO_X can travel hundreds of miles from the place of emission (Andersson et al., 2016). Research shows that more than 70 per cent of marine emissions contribute to air pollution up to 400 km inland, degrading the air quality and the living conditions (McCaffery et al., 2021; Corbett et al., 2007). On a global scale, international maritime transportation is responsible for 13% and 15% of global SO_X and NO_X emissions, respectively. This quantity of pollutants can form concentration hot-spots in the zones of shipping traffic with higher density, which presents a severe risk of significant exposure for coastal populations because ship traffic routes concentrate closer to the coast and around ports (Toscano et al., 2021; Puig et al., 2015; Chen et al., 2018; Ekmekçioğlu et al., 2020; Di Natale and Carotenuto, 2015; Mocerino et al., 2018).

Depending on the service provided, ships spend from several hours to up to several days within port boundaries, during which they use both main and auxiliary engines to provide power for port operations or hoteling. Consequentially, shipping activities cause coastal air quality degradation - as reported by many studies (Viana et al., 2020; Merico et al., 2017; Darbra et al., 2009; Chatzinikolaou et al., 2015; Mao et al., 2020)

Ship emission-related air quality degradation reduces sustainable resources critical to coastal nations that depend on environmentally reliant services like tourism and fishing industries. Coastal areas are popular settlements, with 50% of people in Europe living within 50 kilometres of the coast (Eurostat, 2011), while nearly 2.4 billion people (about 40% of the world's population) live within 100 km of the coast (United Nations, 2018). Therefore, it is vital to quantify emissions from ships and to present the levels of ship emission concentrations spatially. Information about ship emission concentration levels and locations where such emissions are happening are needed to implement measures to mitigate risks for people and the environment.

The impact of ship-related GHG emissions from maritime transport on the global climate and environment is recognised by regulatory bodies; however, at current rates, shipping emissions are not reducing rapidly enough to meet the IMO target for 2050 (Bilgili, 2021). Growth in shipping GHG emissions of 9.6% per year, as reported by the IMO, is happening because maritime transport is growing faster than the reductions in emissions gained by technical measures on ships and existing management and policy measures (Faber et al., 2020). This situation requires regular assessment of ship exhaust emissions both quantitatively and spatially.

Improving the estimation of airborne ship emissions is essential in generating a baseline of information to develop effective mitigation strategies and pollution control policy measures.

2.3 Methodologies for ship exhaust emissions estimate

Ship emissions need to be estimated to gain an understanding of emission quantities to provide evidence that will relate ship types, sizes and technical emissions abatement measures, to CO_2, SO_X and NO_X levels and locations where significant concentrations are generated. Emissions from ships, particularly in the vicinity of cities and densely populated coastal areas, need to be estimated to improve the understanding of ship contributions to overall pollution levels. Accurate quantification of emissions from ships in coastal areas is needed on a regular monthly and yearly basis to understand changes in emission levels and the effect of regulation measures, which is necessary to develop local and regional strategies for emission reduction. It is possible to quantify the emissions from ships using measurements on board, which is the most accurate method; however, that is not practicable for assessing international shipping and shipping in defined geographic areas.

On-board monitoring of emissions from ships generates massive data, which is difficult to process, particularly for international shipping, so emissions need to be estimated (Schim van der Loeff et al., 2018). Current methodologies for ship emissions estimation were reviewed; these can be categorised as *top-down* or *bottom-up* methodologies. *Top-down* methodologies consider assessing airborne emissions for large numbers of vessels in specific local, regional, national or global areas. These methods avoid the need to account for each vessel by sampling similar groups of vessels or using the statistical data averages. Ships are grouped by types, which are further represented by a range of typical technical and navigational values, like engine power or ship cruising speed, respectively. In extensive ship emissions inventories, *top-down* methodologies use national statistics for fuel consumption and shipping traffic inventories. Fuel consumption can be converted to the quantity of emissions using the emission factors. *Bottom-up* methodologies analyse emissions vessel-by-vessel and aggregate results to provide total emissions for the analysed fleet in a particular location. The example of Bottom-up methodology and its application is presented in Chapter 3.

2.4 Emissions factors

Emission factors are obtained using emissions tests during the marine engine production or ship operation stages. Emission factors (EF) can be energy-based and expressed in mass of pollutant per energy [g/kWh], or they can be fuel consumption-based and expressed in mass of pollutant per gram of fuel [g/g fuel]. EFs depend on ship type, fuel chemical composition, type of engine and system {main or auxiliary), engine load and external conditions which impact engine load, like wind, waves, currents and ship hull resistance (Kalli et al., 2013; Jalkanen et al., 2012; Toscano & Murena, 2019).

Emission reduction regulations, policy and technical measures have an impact on changes in overall emissions generated by ships; hence the emission factors will change accordingly.

Policy measures for Nitrogen oxides (NO_x) reduction are regulated by IMO Tier III standard, Regulation 13, which requires all marine engines built after 2016 with installed main engine power greater than 130kW to reduce NOx emissions by 80 per cent compared to Tier I level (Faber et al., 2020). However, the highest abatement measure Tier III is only required for ships operating in NO_x Emission Control Areas (NECA) or ports with individually defined Tier III regulations. Therefore, the difference in regulatory emissions levels for ships complying with different Tier standards according to IMO NOx regulations needs to be considered.

Global NECAs are presented in Figure 2.1. The case study area of this research, the Adriatic Sea is highlighted in the Figure 2.1 as the area that is not included in NECA.

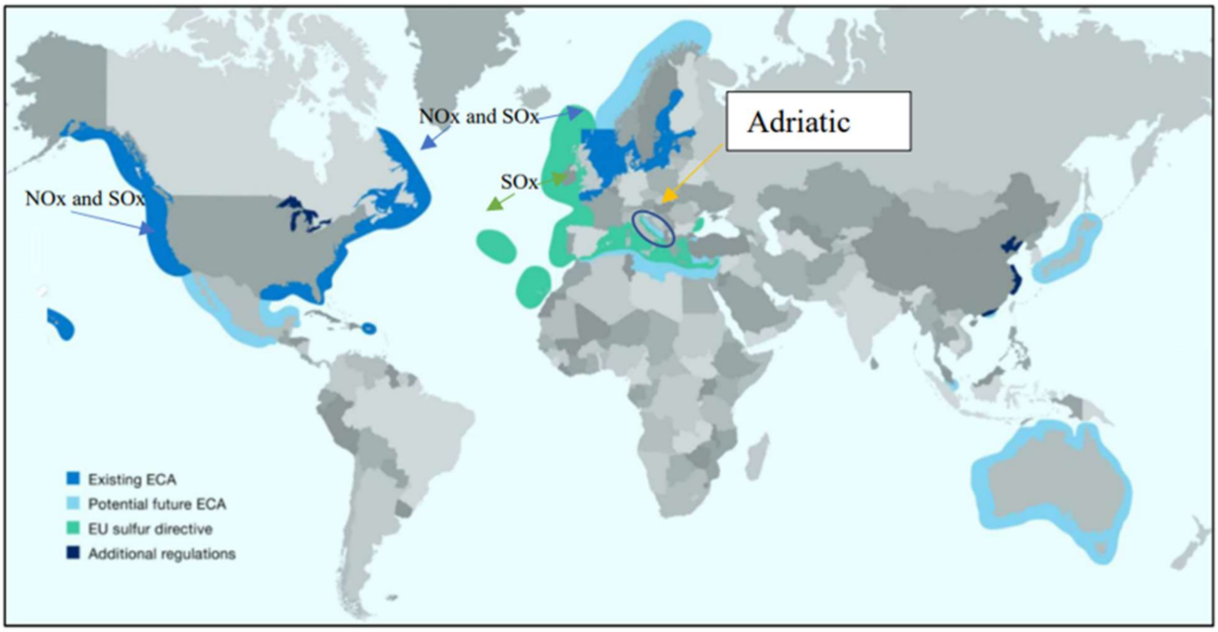

Figure 2. 1: Global NOx and SOx Emissions Control Areas

Emission factors for sulphur are defined by Regulation 14, which sets limits of sulphur content in fuel (IMO 2020 Sulphur Cap), globally and in Sulphur Emission Control Areas (SECAs) (Abadie et al., 2017; Brynolf et al., 2014; EU Commission,2017). From January 2020, the limit for sulphur in fuel oil decreased from 3.5 per cent to 0.5 per cent by mass globally, while in SECAs, which have more stringent requirements for SO_x emissions and sulphur in fuel content, the sulphur cap is set to 0.1 per cent by mass (McCaffery et al., 2021) (Chen et al., 2018). However, recent research shows that the emission reductions achieved by the IMO 2020 Sulphur Cap are not at the desirable level, and the IMO will need to develop new policies inclusive of alternative fuels (Bilgili, 2021; Kuittinen, 2021) and technical measures for emission reduction. The development of new policy measures will require evidence of current ship emissions and practical and accurate methodology to assess emissions and analyse policy measures' effectiveness.

Policy measures regulate emission limits and stipulate shipping stakeholders' implementation of technical measures. Technical measures on ships using diesel engines can improve engine efficiency to keep NO_X emissions within the allowed limits, which will impact NO_X emission factors.

Technical measures for SO_X reduction include the installation of scrubbers and catalytic recirculation systems or retrofitting the engine to use alternative fuels. Some analyses (Li et al., 2020) show that ship operators' preferred sulphur abatement measures are:

1) switching to low sulphur fuels (under 0.5 per cent globally or 0.1 per cent in SECA and EU ports)

2) installing exhaust gas cleaning systems

3) running on alternative fuels, e.g., liquefied natural gas (LNG).

Primary drivers for ship operators' choice are cost benefits; for example, scrubber installation is more suitable for new ships and those with a remaining lifespan equalling the lifespan of the scrubbers (Zhao et al., 2021). Choice of technical measures will broadly impact emission factors.

Emission factors are used in conjunction with ship fuel consumption or energy demand to estimate emissions from ship exhausts (Scarbrough et al., 2017). Emission factors vary with engine power and size, which is best identified by measurements; however, measurements during ship operation are difficult to obtain or process. Methodologies for ship emission estimates use different approaches to obtain emission factors.

Bottom-up methodologies using on-board exhaust emissions measurements and marine engine process modelling typically focus on a limited number of vessels to establish fuel consumption and emission factors in different navigational conditions (Tavakoli et al., 2020).

A new set of emission factors were proposed by Jahangiri et al (2018) during 11 days of emission measurement on-board two ocean-going vessels, with results compared for at berth, manoeuvring and cruising conditions. Engine loads influenced EFs, particularly during harbour manoeuvring, as at low loads, marine engines might generate higher emissions, particularly NOx, due to the dependency of pollutant formation to combustion process temperature (McCaffery et al., 2021).

This was also confirmed in Trodden et al. (2015) and Trodden & Haroutunian (2018) studies on NO_x emission factors for a ship during manoeuvring. The methodology compares measurements to simulations of NO_x emissions generated by LNG-fuelled diesel cycle engines in calm water for dead-ahead and manoeuvring conditions. The value of NO_2 formation, estimated for the manoeuvring operation, was nearly four times that of the steady-state estimate. The advantage of this method is that the emission factors obtained to provide a reference for numerical modelling also provide a good reference for the particular ship type. The disadvantage is that such measurements are costly and impossible to obtain for regional shipping traffic in sea-going conditions. Measurements on-board ships are time-consuming and require consent from ship owners, expensive measuring equipment, highly skilled operators and complex data analyses. Those analyses are used as a reference for numerical models; however, they require the processing of massive datasets.

On-board emission measurements were carried out to obtain emission factors for sample ships, each representing a different ship type (Yang et al., 2021), using a portable emission measurement system (PEMS). The study shows that pollutants from ship exhausts, NOx and SOx, have the greatest impact in the Tianjin port area, where ships tend to manoeuvre when compared to areas where ships are in cruising operational mode.

Research by McCaffery et al. (2021) uses actual on-board measurements and quantifies air pollutants from the exhaust of two containerships that are classed as tier 2 by IMO NO_x standard (Faber et al., 2020). The study compares emission factors for two ECA compliant fuels and demonstrates the potential global benefit of using ultra-low sulphur residue fuels. Results show that near port emissions of NO_x from the tested very low sulphur marine gas oil (VLSMGO) and ultra-low sulphur heavy fuel oil (ULSHFO) will likely increase compared to middle distillate fuels (MGO), concluding that VLSFO significantly reduces the emission of $SO_{x;}$ however, it produces higher NO_x values. This methodology provides a precise analysis of the impact of the choice of fuel on the emissions of two containerships. This is, however, not a large enough sample to use the obtained emission factors as a proxy for the ship type emission factors.

Ship exhaust emission measurements were obtained for specific engine loads (between 9% and 45%), representing low-speed ship operations such as vessel speed reduction in port areas, port manoeuvring or cruising (McCaffery et al., 2021).

The method used by Goldsworthy et al. (2015) uses empirical methods to measure the emissions of a sample of ships at the engine exhaust system and compares the results to those obtained from the model based on calculations using AIS data.

Most other methods use published emission factor estimates for different fuels and engine loads. For example, Toscano et al. (2021) use statistical databases in combination with databases obtained by measurements on board ships (EEA, 2019; ENTEC, 2002; ENTEC, 2007).

Emission factors are obtained by measurements or from an extensive database created by the IMO (Chapter 1, section 1.1). The IMO uses vessel-based data obtained from port authorities, the coast guard, ship owners' databases and other available sources to establish ship technical characteristics. Additionally, the IMO (2014, 2020) has performed extensive measurements on-board ships, which resulted in the statistical database of emission factors for all commercial ship types, sizes, and engine powers. Ships are clustered in ship types sharing constant estimated median values for some of the factors used in emission calculation: speed, fuel consumption, main engine power, load or emission coefficient. This represents a valuable statistical data source that can reduce the cost and time of obtaining average global population statistics for ship types, such as sea-going speed. Emission factors developed by the IMO are widely adopted and applied in methodologies for ship emission estimation (Olmer et al., 2017; Merk, 2014a; McCaffery et al., 2021).

The disadvantage of data acquisition using measurements is that it is expensive in terms of the resources required to analyse hundreds of ships across all ship types and sizes. The high level of expertise and skillsets necessary to achieve this requires a team of experts and complex data acquisition and processing, making this methodology impossible for most businesses and institutions. The robust global study by the IMO is based on the continuous research of thousands of ships over 26 years since 1996 and thus presents the most extensive publicly available ship operational parameter statistics. Based on this evidence, the IMO has established regulatory emission levels, which are either energy-based and expressed in g/kWh or based on fuel consumption and expressed as grams of pollutant per gram of fuel consumed.

This Thesis research uses energy-based emission factors because fuel consumption is not known, and energy-based emission factors can convert to specific fuel consumption factors (SFOC) for corresponding engine power and RPM. Fuel consumption is unknown because the research scope is an assessment of ship emissions in geographic areas using a massive number of ships, which makes the acquisition of detailed fuel consumption data impossible. Additionally, the research objective is to quantify emissions based on ship energy demand, which requires energy-based emission factors.

In this Thesis, emission factors were assumed to be maximal regulatory limits, considering technical measures on-board ships to understand how those measures impact ship emission levels, which could provide evidence about regulation effectiveness.

A more detailed explanation of relevant parameters applied to estimate emissions from ships is presented in Chapters 3 and 4, which explain emission estimation models. The next section presents a general overview of methodologies, their objectives and limitations.

2.5 Review of top-down methodologies

Top-down methods provide estimates on global and national levels. These methods use the aggregation of fleet-scale data as a proxy for emissions to estimate the contribution of a fleet of ships to overall emissions. Top-down methods use data resources that are not publically available, like fuel sales or consumption data.

The *top-down* methodology by Ricardo Energy & Environment uses information on marine fuel consumption at national levels to provide estimates for the national shipping emissions inventory for the UK (Scarbrough et al., 2017). This provides an estimate of total national shipping traffic emissions, where fuel consumption is assigned to ship types, represented by typical values for the average vessel in the group. This methodology generated national inventory GHG totals for air pollutant emissions reported to UNFCCC and EU in 2017.

The limitation of using national fuel consumption data is the absence of information for international shipping. Additionally, top- down approach creates aggregated results which cannot be down-scaled to accurately estimate emissions of regional and local port boundary areas. Therefore, the study uses such values for comparison with more detailed vessel-based *bottom-up* analyses, which require high investment in a multidisciplinary team of experts, access to publicly restricted data and complex data processing. This methodology provides an estimate of the conversion of fuel sold to emissions; however, it is not accurate enough to provide evidence of local emissions concentrations, the contribution of transiting ships, exact polluting ship type or the relation between emission quantities and technical measures on-board ships.

The IMO provides a guide for rapid emissions assessment in the national context through the Port Emissions Toolkit Guide and suggested National ship emissions reduction strategy. The guide called the Ship Emissions Toolkit Guide is the third out of three guides by the GloMEEP Project, which is a cooperative initiative of the Global Environment Facility (GEF), the United Nations Development Programme (UNDP) and the International Maritime Organization (IMO) to assist developing countries in the uptake and implementation of energy efficiency measures for shipping and preventing of air pollution from shipping (GEF-UNDP-IMO GloMEEP Project and IMarEST, 2018b). This IMO guide provides tools and a methodology for emission estimation, which encourages national decision-making bodies, policymakers and legislators to incorporate MARPOL Annex VI regulations into domestic laws. To follow the guidelines, countries complying with the regulations need a tool to survey emissions from ships in their geographic area. The methodology is needed for verification and monitoring that each signatory state should implement to ascertain the convention is met.

Local authorities need to receive enough evidence of emissions from shipping to estimate whether the local area complies with IMO ship emissions targets and regulations.

Another *top-down* approach by Toscano & Murena (2019) reviews yearly emissions of NOx and PM10 in ports by analyses of scientific papers and port reports on ship and traffic emissions, using the regression equations to systematise incompatible datasets. The problem with published journal papers and reports is that data on emissions from ships is not homogenous, making it difficult to compare or systematise. For example, a difference in emissions reporting is found in the usage of different EFs for sulphur, which depends on sulphur content in the fuel and ranges from 0.1% to 2.7%, depending on the year and geographical area. Another difference was in the length of the ship navigation distance considered; some authors consider the distance from the port boundary to the berth; others include wider shipping approach areas to understand the impact on the city areas.

A further difficulty in assessing emissions using published emissions quantities is not comparably presented data. For example, emissions can be expressed per passenger for passenger ships or differently defined vessel categories. Therefore, the authors Toscano & Murena (2019) have developed a statistical regression equation to compare and systematise different emission estimation datasets published across journals and port reports. This method's statistical regression equations can enable the comparison and compilation of different datasets. The author presents data correlation reliability for compared emissions reports, which vary from “low” to intermediate. The methodology provides a robust systematisation of publicly available ship emission reports; however, the emission quantification accuracy depends on the amount and quality of published data available, which is a limitation that makes such estimates inadequate for emission reporting or understanding of emissions measures effectiveness.

A *top-down* approach combined with a *bottom-up* method was used to calculate a ship emission inventory for Chinese inland river waterways (Peng et al., 2020). This *top-down* method is compared to a *bottom-up* methodology that is used to estimate emissions for ship samples. The sample size is decided based on the ship’s temporal traffic density. Quantified emissions for the sample are then applied to the population based on the ship type and estimated main engine power. Engine load factor is estimated for ship size bins for different ship types, while Emission

Factors (EF) are input from other studies. This method was applied successfully in the Yangtze River, where ship density is amongst the highest globally, and it was reported that ship tracking by Automatic Identification System (AIS) often had missing data due to high traffic density. This method reduces uncertainties of missing data in dense shipping areas and provides adequate inventories for a population of over 20,500 ships and data samples of 10 per cent. However, this method does not present the spatial distribution of ship exhaust inventories.

The top-down approach of Scarbrough et al. (2017) uses fuel consumption data, engine manufacturer data and data from the Lloyd's Register of Shipping database. The ship activity data thus acquired is used to estimate CO_2, CH_4, N_2O, SO_2, NO_X, PM, NMVOC and CO emissions generated by ship diesel engines. The advantage of this methodology is the ability to estimate emissions for many ships; however, assumptions based on fuel consumption data do not provide a clear understanding of where emissions are generated. The methodology provides the emissions inventory for the UK domestic and international shipping transiting or bypassing the UK. The disadvantage is the low resolution of emission estimates at the regional level, which makes this methodology inadequate for assessing emissions in regional seas and ports.

2.6 Review of bottom-up methodologies

Bottom-up methodologies observe individual vessels and present a closer estimate of actual measurements on-board the ship. Different *bottom-up* methodologies use different parameters to understand ship navigational and technical characteristics; however, some *bottom-up* methodologies take into consideration external influences that impact ship speed and, consequentially, its engine load. Detailed bottom-up methodologies using measurements, either on-board or in laboratory conditions, can be classed as empirical.

Bottom-up methodologies are based on measurements and estimates for single vessels, referred to as a 'vessel-based' approach. Vessel-based emission estimation approaches can be fuel consumption-based or energy demand-based. Based on newly adopted legislation to monitor, verify and report CO_2 emissions (Regulation (EU) 2015/757), *bottom-up* emission reporting now exists (EU Commission, 2020b) that utilises restricted data from ship operators' CO_2 emission reports. However, this data is limited and difficult for third parties to access, which is why emission inventories for regional areas rely on emission estimates.

According to the IMO (GEF-UNDP-IMO GloMEEP Project and IMarEST, 2018a), for rapid assessment of ship emissions, *bottom-up* method accuracy is best achieved by assessing shipping activity to produce calculation models for energy consumption. This method estimates fuel consumption and emissions using data sources that describe shipping activity and ship technical characteristics.

Bottom-up ship emission estimation methods that use AIS data are the closest alternative to emissions measurements during ship operations. *Bottom-up* methods may use instantaneous AIS data, which is free or historical AIS data, which can be through commercial portals or obtained through cooperation with organisations that provide access to such data, such as marine safety institutions.

The comprehensive *bottom-up* modelling using the Ship Traffic Emission Assessment Model (STEAM) by Jalkanen et al. (2009) and Kalli et al. (2013) was demonstrated on European seas and reported by Jalkanen et al. (2016) and Kuittinen et al. (2021). This model uses detailed vessel technical information and historical AIS data to individually determine fuel consumption and emissions for each vessel, which is then aggregated to form the regional ship emissions inventory, with about one per cent of the information obtained by measurements on-board sample vessels. The model presents ship CO_2 emission intensity and hotspots on a spatial map. This method is a result of the cooperation of large organisations in charge of relevant historic AIS datasets (European Maritime Safety Agency, European Space Agency, Norwegian Coastal Administration and others). These organisations in charge of recording have also provided historical AIS data information for the purpose of national inventories. However, such datasets are not publicly available.

A model by Goldsworthy and Goldsworthy (2015) uses AIS to detect the movements of ships around the coast of Australia. Data is first filtered for anomalies, after which ship operating modes are assigned. Gaps in the data are filled by interpolation between two consecutive AIS points. This system was further improved by Goldsworthy (2017) by using an interpolation method, which steers interpolated tracks moving close to the shore to follow the geographical features of the coast more naturally. The interpolation of ship tracks uses AIS signals recorded in specific time intervals. If time intervals are variable or more prolonged than acceptable (depending on methodology needs, ship activity and geographical location), missing data is replaced by either (1) the shortest distance between two points or (2) the knowledge database of clustered points of call for the location. The method used by Goldsworthy (2017) uses both the first and second missing data replacement systems. The limitation of the first choice is that this method can only be applied for open sea cruising activity, where no land and no obstacles exist between two successive points of call. The limitation of the second choice is that obstacles between two AIS points of call are avoided using straight-line connectors, which can differ from actual shipping route. This limitation was resolved in this Thesis by the newly developed SEA method, which is using one-year of historic ship tracks to identify average shipping route. This route is estimated as the route of highest probability and it follows actual shipping lanes typically used by ships of same type and size range. This is explained further in Chapter 4.

The methodology by Pallotta (2013) uses probabilistic modelling to estimate and improve interpolation with straight lines. This methodology uses the TREAD algorithm (Traffic Route Extraction and Anomaly Detection), which is thought to progressively update the route patterns knowledge database and replace malfunctioning or missing data with patterns selected from the knowledge database using a probability algorithm. This methodology collects data from historical shipping tracks to update single ship voyage gaps in data. This presents a limitation because it becomes data and time inefficient if estimates are needed for many ships. This approach needed simplification, which was further explored by the novel SEA methodology.

Ship AIS signals are collected and presented as aggregated data of ship movements by widely accessible commercial platforms (Marine Traffic, 2019). Aggregated data of ship movements reveals actual ship movement patterns without the further need for vessel-by-vessel trajectory estimates. Ship points of call are clustered in aggregated patterns, which precisely show the positions of ships over one year at the observed location. Such data can be filtered for specific ship types.

Clusters of unprocessed ship points of call are gathered in the knowledge database by Clarkson's Research commercial platform and presented on the scalable global map (Clarkson's Research, 2019). The research for this Thesis attempted to apply previously unused data in ship emissions estimates to understand ship movement patterns and reduce the time needed to produce ship trajectories.

A *bottom-up*, AIS based methodology developed by Huang et al. (2017) compares estimated exhaust emission estimates for 12 containership voyages to emission estimates based on the fuel consumption data obtained from the ship operator. This method uses estimates of engine power based on ship size and type however does not account for any additional technical measures installed. Results are presented in a spatial-temporal map, with a time of day and month when emissions are peaking and the highest emission ship types in the Chinese port of Ningbo-Zhoushan. This method is valuable for providing evidence to improve the efficiency of managerial measures for emission control. Managerial measures for emission reduction can, for example, efficiently cut CO_2 emissions by reinforcing cruising speed limits. However, this methodology could be improved further to provide more detailed knowledge of the efficiency of technical and policy measures.

Further improvements were conducted in the next study by the same author Huang et al. (2020), where a bottom-up model was used to identify ship voyage emission peaks, presented spatially, while the ship emission inventory was expanded from a single port to the regional area. Again, this method reveals peak emissions periods for vessels and claims to be applicable to real-time emissions estimation. The methodology can improve ship traffic management; however, it does not provide a clear link between the technical measures on-board ships and emissions. Therefore, this methodology cannot be used to forecast or assess policy measures for SOx and NOx effectiveness.

Some *bottom-up* AIS based ship emission estimates have been used in atmospheric research, air quality and dispersion modelling. For example, a *bottom-up* approach for the port of Naples by Toscano et al. (2021) uses AIS to obtain an hourly record of ship activities, classified as navigation during arrival or departure and hoteling at berth; and quantifies NO_x, SO_2, and PM emission rates, in tonnes of pollutant emitted per year. However, atmospheric modelling software obtains the spatial distribution of emissions by using the input data obtained by measurements at ground monitoring stations in and around the port. Technical emission reduction measures on-board ships and year of build are not considered to differentiate emission factors. This modelling can provide an understanding of atmospheric dispersion of emissions within the local area; however, it does not indicate the existence of emissions abatement technical and policy measures or how effective those measures are.

Another *bottom-up* methodology by Chen et al. (2021) also evaluates AIS data instantaneously, extracting trajectories of ship moves in the Arctic region. This method provided average speeds of ships and showed them to be higher than those recommended by the Polar Code slow steaming regulations. Trajectories were further used to test scenarios in which emission factors for different types of fuels were applied. Similar to previous studies, this study does not consider onboard emission reduction measures, and it is not adequate to identify the effect of policy measures on emissions from ships.

The research by Brynolf et al. (2014) analyses compliance with ECA regulations using abatement technologies or change of fuel. Brynolf's research obtained statistical data regarding ship fuel usage (HFO, MGO or LNG) through direct communication with the engine manufacturer, Wärtsilä. Obtaining the fuel type and consumption data through direct contact with shipping companies requires long-term cooperation and building trust, collaboration on a joint project and an established business network. The approach obtains high-quality data; however, this data is not publicly available and requires well-developed communication with ports and shipping stakeholders, which can be challenging or impossible in some regions, especially if different countries share the same coastline, and international port traffic needs to assess emissions, as in the case study presented in Chapter 6.

The method used by McCaffery et al. (2021) analyses CO_2, SO_x, NO_x, black carbon (BC) and particulate matter (PM) emissions for operations of two containership vessels and provides detailed emission factor analysis for all ship phases. The advantage of this methodology is that it provides emission factors of NO_x for sea-going conditions, which cannot be obtained in laboratory conditions. Emissions of CO_2 and SO_2 correlate with fuel consumption due to carbon and sulphur content in fuel; however, NO_X is not explicitly related to the fuel chemistry but rather combustion conditions. Therefore, measurements in sea conditions improve the understanding of emission factors of sea-going vessels. However, this type of detailed measurement on-board requires either individual ship sea trials, which is rare or following the ship during its operations. The latter produces a massive amount of data that is difficult to process as it requires complex filtering just to generate data for emissions from a single ship. The method was used to analyse two ships, which is too small a sample to cover variation in ship size or ship type. Additionally, this methodology is not appropriate for assessing local areas, ports or ships in transit.

The bottom-up approach developed by the IMO (2020) uses AIS source data to identify ship speed, position and course, which is needed to understand how much time ships spend in each activity phase, cruising, manoeuvring, and anchoring or at berth. This method is detailed and well-evidenced to provide accurate estimates for individual ship voyages. Hence, this method (Section 2.2, Chapter 1, section 1.1) was used as a reference model in this research, which is further explained in Chapter 3.

The Ship Energy Efficiency Management Plan (SEEMP) is applied through the IMO's convention using Energy Efficiency Operational Indicator (EEOI) for preventing pollution at sea, MARPOL, as a regulatory measure for CO_2 mitigation on all existing ships (Peralta, 2018). There are two essential emission regulations, and these are European Union Monitoring, Reporting and Verification (EU-MRV) and International Maritime Organization Data Collection System (IMO

DCS). Also, the Ship Energy Efficiency Management Plan (SEEMP) Part 2 became valid from 2018 to 2019 (Abadie et al., 2017). SEEMP sets plans for measuring a ship's fuel consumption, which is directly linked to CO_2 ship emissions, and, subsequently, the EEOI. This regulatory measure enables ship operators to calculate ship emissions; however, such data is not publicly available.

Data from EU-MRV ship emission monitoring programs is not publicly available for scientific analysis. The first report published in EU Regulation on monitoring, reporting and verification (MRV) in 2018 provides emissions quantification on a national level, but it lacks the resolution needed for emission inventories for ports and local coastal areas (ESSF, 2017).

Referencing levels for CO_2 were established based on 11,600 ships in 2018 (EU Commission, 2020a). When added up, those ships represented over 138 million tonnes of CO_2 emissions in that year, equating to 3.7% of total CO_2 in the EU area. The EU MRV report compared CO_2 emissions across different ship types and concluded that container ships are responsible for the largest share of total emissions, representing over 30% of emissions (EU Commission, 2020b).

The main issue for an assessment needed for evidence of the impact of ship emissions on air quality, and consequentially people and the environment, is the lack of data on the estimation of emissions (Toscano et al., 2021). Initiatives to encourage voluntary reporting mechanisms on fuel consumption, for example, the Clean Cargo initiative for containerships by Godet et al. (2021), are still in the early proposal stage and limited to specific business to business information exchanges.

Quantification of emissions is necessary for the development and improvement of policy measures, which need further development to stimulate stakeholders on rapid emission reduction measures to reach current IMO regulations as a minimum and increase awareness and readiness towards the net-Zero targets, following the example of the UK that has introduced net-Zero targets as a National strategy (BEIS, 2020). Emission quantification and a deeper understanding of their distribution are essential in the evaluation of the effectiveness of technical measures and emission reduction strategies. The global shipping community needs a methodology that is time-effective and low-cost and can be used regularly to estimate and manage port or regional sea ship emission inventories.

2.7 Summary of Chapter 2

This chapter presents the research background that explains why CO_2, SO_X and NO_X emissions generated by ships present a global concern, in particular in densely populated port cities and coastal areas. The literature review of current methodologies for ship emissions assessment was conducted with regard to assessing ship emissions in local regions, ports or coastal waters. However, the current methodologies were either top-down and rapid but not accurate enough for the selected purpose or accurate and detailed, vessel-based bottom-up methods that are expensive and not practical for the purpose of geographic location time-effective emission estimates. The identified gap between the top-down and bottom-up methodologies needs filling with a methodology which is capable of rapid estimates of emissions from ships in geographic areas, which would be accurate enough to assess the efficiency of regulatory emission abatement measures.

Chapter 3. Implementation of the Bottom-up Model

3.1. Introduction to Chapter 3

IMO developed a bottom-up emission prediction model to estimate emissions from ship exhausts for different pollutants. This chapter presents the implementation of the bottom-up IMO methodology model (referred to in the further text as the Bottom-up model) to estimate CO_2, SO_X and NO_X emissions for the selected case study ships, in this case, containerships. The Bottom-up model is used to produce accurate estimates of emissions from ship exhausts, using the AIS system to identify ship location and speed. The initial database of accurate emission estimates was developed as a reference for further research. The Bottom-up model was further used to validate the SEA model (Chapter 4), as presented in Chapter 5. The reasons for selecting the Bottom-up model and parameters used to estimate vessel-based emissions are explained in section 3.2. The Bottom-up model uses the 8-step process, which is explained and presented with the model diagram in section 3.4.

3.2 Key parameters in the Bottom-up model for ship emission estimate

The Bottom-up model was developed to get a detailed insight into ship technical characteristics and external parameters that affect emission generation.

The key parameters needed to estimate emissions from ships are the ship energy demand and the emission factors for each pollutant emitted. Equation 3.1 presents how exhaust emissions are quantified as a product of energy demand measured in kWh and emission factor in grams per kWh of energy.

Emission Quantity [g] = Ship Energy Demand [kWh] x Emission Factor [g/kWh] *(3.1)*

Energy demand is variable and depends on the activity phase that the ship is engaged with; these were identified as: cruising, manoeuvring, anchoring or berthing, which includes cargo operations in port. Ship energy generated by the burning of fuel would be expended differently in different phases. For the purpose of this research, it was assumed that main engines in all case studies were used for propulsion only, while auxiliary engines were used for the power supply needed for ship hoteling and supporting services, which is a common practice by ships approaching and departing from the port and during the port operations. The Bottom-up model uses AIS signals to detect ship speed over the ground and uses this to estimate ship activity phase and energy demand, which is explained further in section 3.3.

Emission factors for CO_2 and SO_X relate to engine fuel consumption properties because emission quantities of CO_2 and SO_X depend directly on fuel consumption. Emission factors for NOx relate to the engine combustion process characteristics because NO_X is not a fuel chemical component. Its formation depends on the temperatures developed during the combustion process and the duration of critically elevated temperatures in the combustion process. Therefore, amongst other parameters, emission factors for NO_X depend on the engine's ability to meet the regulation requirements. Marine engines built after 2016 are required to comply with IMO Tier III regulatory NOx emissions levels.

Since the research aims to understand the effectiveness of current and future emission regulations, it was assumed that ships emit maximum legally permitted quantities of pollutants for the ship type or expected permitted quantities considering the installed technical reduction measures. These permitted NO_X quantities were used in both computational models developed for this research: the Bottom-up and the SEA model. Regulatory emission factors are further explained and presented in Section 4.3.3.

3.3 Data acquisition for the Bottom-up Model

The Bottom-up model presented in this chapter needed a historical ship activity AIS dataset for the activity of ships in the geographical area. Data containing geographic location, timestamp, speed and course of the ship for every AIS signal can be collected instantaneously, which is free of charge service; however, this requires additional cost in terms of time which is needed to complete data acquisition. Otherwise, data can be purchased as historical datasets obtained through the Marine Traffic (2019) system and Clarkson's Research (2019), which are publicly available commercial portals.

A historical AIS dataset is defined by the ship name and location, or ship name and historical time period. One voyage dataset was defined as a set of AIS data points received from ship entry to its exit of the research boundary, which in this Thesis research includes its berthing phase in the port. Each voyage dataset for the Bottom-up model consisted of a number of AIS data records. The size of the AIS data package depends on the number of AIS data records, which depends on the ship voyage period and time resolution. If the ship is followed for 1.5 days during transit to and out of the port, where it remains less than 24h, the number of AIS records could vary between 300 to 800 for the variable time resolution of 1 to 30-minute gaps between two consecutive AIS signals.

For the purpose of this research, the objective was to obtain an AIS dataset with resolution between 1 to 5 minutes during the ship transit (cruising and manoeuvring) and 5min to 30min while the ship is in berth to achieve optimal accuracy and reduce dataset acquisition costs. Historical dataset prices depend on the number of records of AIS signals in the set, so reducing the dataset size to the accuracy required for the methodology reduces costs.

3.4 The Bottom-up Model

The Bottom-up model is presented in the flow diagram in this section in Figure 3.1. The Bottom-up model is explained through eight steps; each step is specified by Roman numerals and colours, listed in the legend in the top right corner of Figure 3.1.

Steps from I to III mainly focus on data input and boundary condition, which is further explained in Sections 3.4.1 to 3.4.3. Bottom-up model equations to obtain energy demand are part of the eight steps explained in Section 3.4.7. Key parameters feeding the equations are ship emission factors and ship engine load, which are explained in Sections 3.4.5 and 3.4.6.

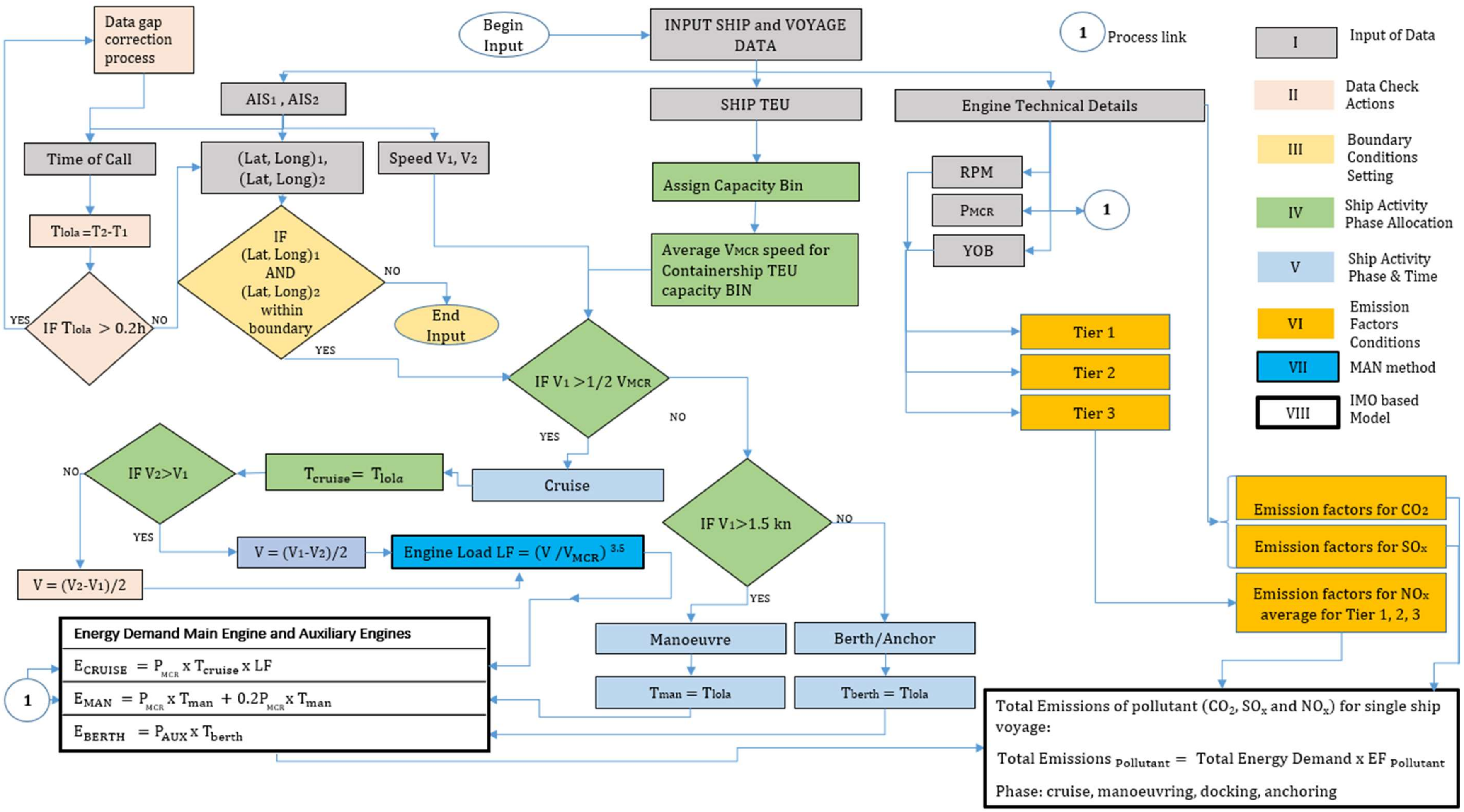

Figure 3. 1: The Bottom-up model schematic diagram

The key to the symbols used in Figure 3.1 is:

$(Lat, Long)_1$ and $(Lat, Long)_2$ – AIS readings of ship geographical position (latitude and longitude) for two consecutive AIS points

V – ship speed [kn/h]

V_1 and V_2 – ship speeds detected between the two consecutive AIS signals [kn/h]

T_1 and T_2 – the time of two consecutive AIS signals [time is received in the format of hh:mm:ss, which is then converted to seconds]

T_{lola} – time elapsed between the two consecutive AIS signals [s]

T_{cruise} – time ship spends in cruising phase [s]

T_{man} – time ship spends in manoeuvring phase [s]

T_{berth} – time ship spends at berth [s]

The legend in Figure 3.1 visually presents eight steps of the bottom-up model, which are explained in the following section.

3.4.1 Step I: Input of data

Ship AIS transmitters emit AIS signals received in constant or variable time resolution by satellite or land-based VHF stations, and each signal contains an AIS data record that comprises timestamp, location, ship speed, and course. In the case of real-time AIS data gathering, a single unit for AIS data is an AIS signal or AIS point of call, while for historical data, an AIS signal is referred to as an AIS data record or AIS record.

The processing of the data obtained from AIS is explained in this section.

Input to the computational model requires the following:

1) Time of call
2) Speed overground

A) Time of call

The ‘Time of call’ or Timestamp is the key temporal parameter used to estimate the time a ship spends in activity phases and input to the ship energy efficiency estimation equations (Figure 3.1).

The historical AIS records were obtained for the case study ships calling at the researched ports. The temporal resolution of AIS records was one minute during the cruising and manoeuvring phases and thirty minutes in the berth phase. However, purchased AIS records contained duplicated and erroneous records, which needed to be filtered before inputting data to the bottom-up model. This filtering was completed by searching for multiple records with the same time of record received or ‘time of call’, which were then deleted to keep just one. The erroneous data, which consisted of multiple records with impossible speed or location data, was deleted, and in most cases, the deletion of errors did not cause gaps in the data. Gaps in data appeared in less than 5% of cases and this was resolved as explained in Section 3.4.2.

B) Speed

Ship speed is detected by AIS as speed over the ground, which is the actual ship speed in the absence of external conditions. The main objective of this method is to understand energy consumption and ultimately estimate fuel consumption. Ship speed is used to identify ship activity phase and estimate ship engine load.

Additionally, ship speed was used to estimate the time a ship spends in each activity phase.

3.4.2 Step II: Data check actions

Data received through the AIS needs checking for errors and gaps, as shown in Figure 3.1. The time elapsed between two successive AIS signals and ship speed over the ground determine the ship activity phase.

The vessel-based model was applied to build a database of estimated emissions for ship voyages. The database of detailed bottom-up vessel-based estimates for samples of ship voyages with one to five minutes temporal resolution was used to verify results in further research. Vessels were chosen with the highest number of visits to the same port, with a constant temporal resolution of AIS signals.

Firstly, two containership vessels were selected that had data for a total of 20 voyages to the same port throughout different periods of the year (to include possible seasonal fluctuations). Temporal resolution for this sample was variable from 1 to 12 minutes.

Secondly, a more significant sample of 75 containerships was tested at the same port over a one-year period. The temporal resolution for this sample of 75 containerships was 30 minutes to one hour—the sample of 75 containerships' one-year voyages to the same port contained over 9,000 AIS data records. The number of data records dropped by 1,500 after filtering out erroneous data and repeated signals. Repeated signals appear when AIS land stations capture the same AIS message from the same vessel; however, the system records it incorrectly as two different records. Such records have the same time of call, which is filtered before the input of data.

An algorithm to detect gaps in the temporal continuity of AIS signals was used to allocate errors. Gaps in data were replaced by comparing different sources of historical AIS record data: Marine Traffic and Clarkson's Research. If a gap existed across both platforms, a ship activity phase was estimated based on average ship speed between successive points of call. The shortest distance between two points of call was used to establish the time lapsed in the cruising phase, as T_{cruise} is the distance divided by the speed average.

3.4.3 Step III: Boundary condition

Observation of historic ship tracks for case study ports of Venice, Trieste and Rijeka (rationale for case study area is explained in Chapter 6) show that all containerships in transit within the 20nm from the ports call to those ports. Therefore, emissions generated by containerships within 20nm from those ports strictly depend on the efficiency of those selected ports to process shipping operations, regulatory measures of the local area and technical measures installed on-board ships calling to selected ports.

The boundary's longitude and latitude are checked by comparison to the ship's position detected by AIS. A boundary was set at 20 nautical miles from the port, as presented in Figure 3.2.

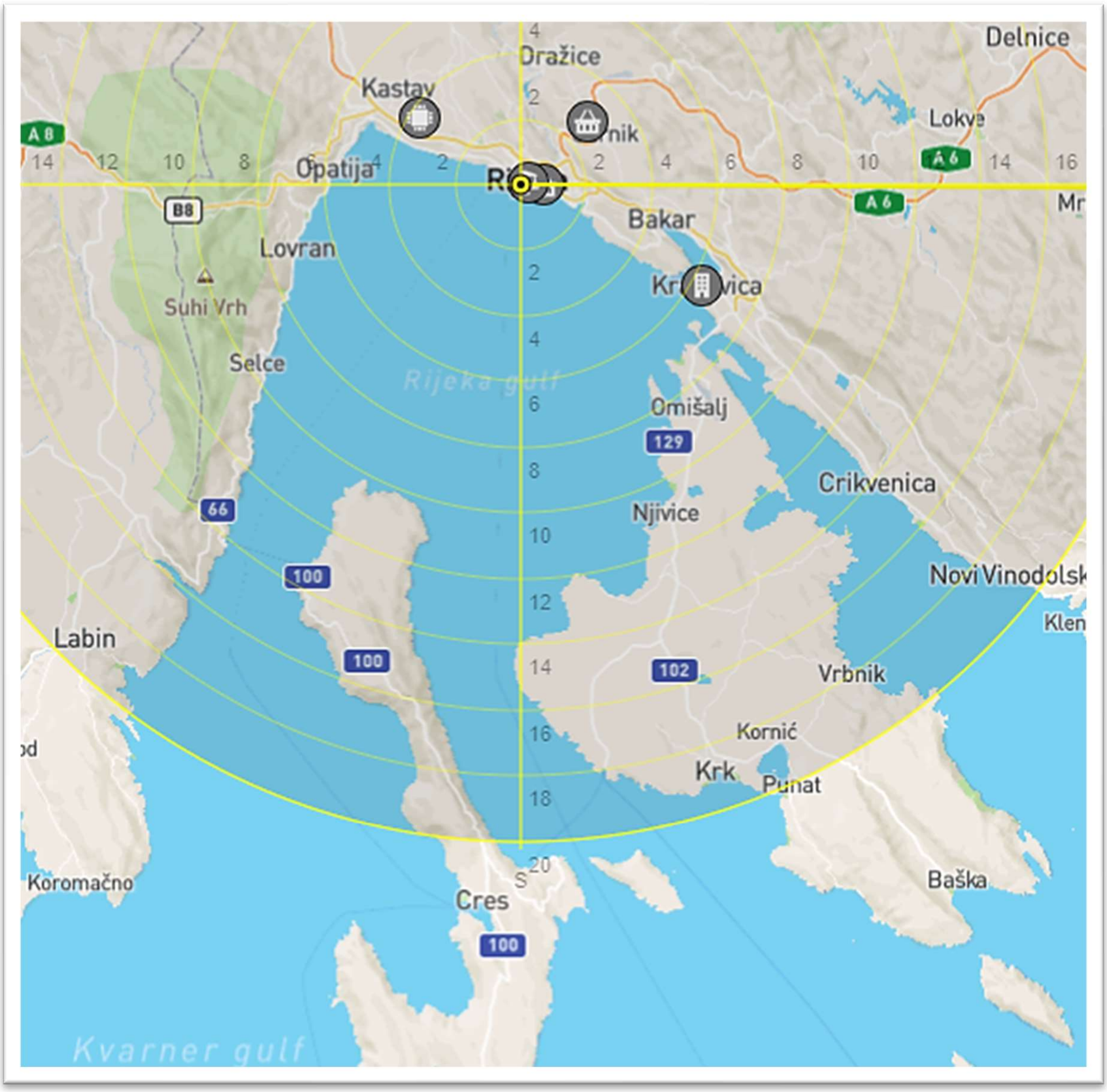

Figure 3. 2: Research geographic area measured radially 20nm from the port is presented for the Port of Rijeka; as an example

The first AIS signal received from the ship calling at the port, considered as an input to the Bottom-up model for emission assessment, would be the first one within the boundary zone closest to the boundary. An example is presented in Figure 3.3, which explains how the bottom-up model considers ship location data detected by AIS signals when the signal is close to the boundary area. However, the closest AIS point to the boundary is rarely at the boundary itself, so the distance the ship has travelled from the boundary to the first AIS signal location was estimated. This process is termed 'correction of distance' and is presented in Figure 3.3.

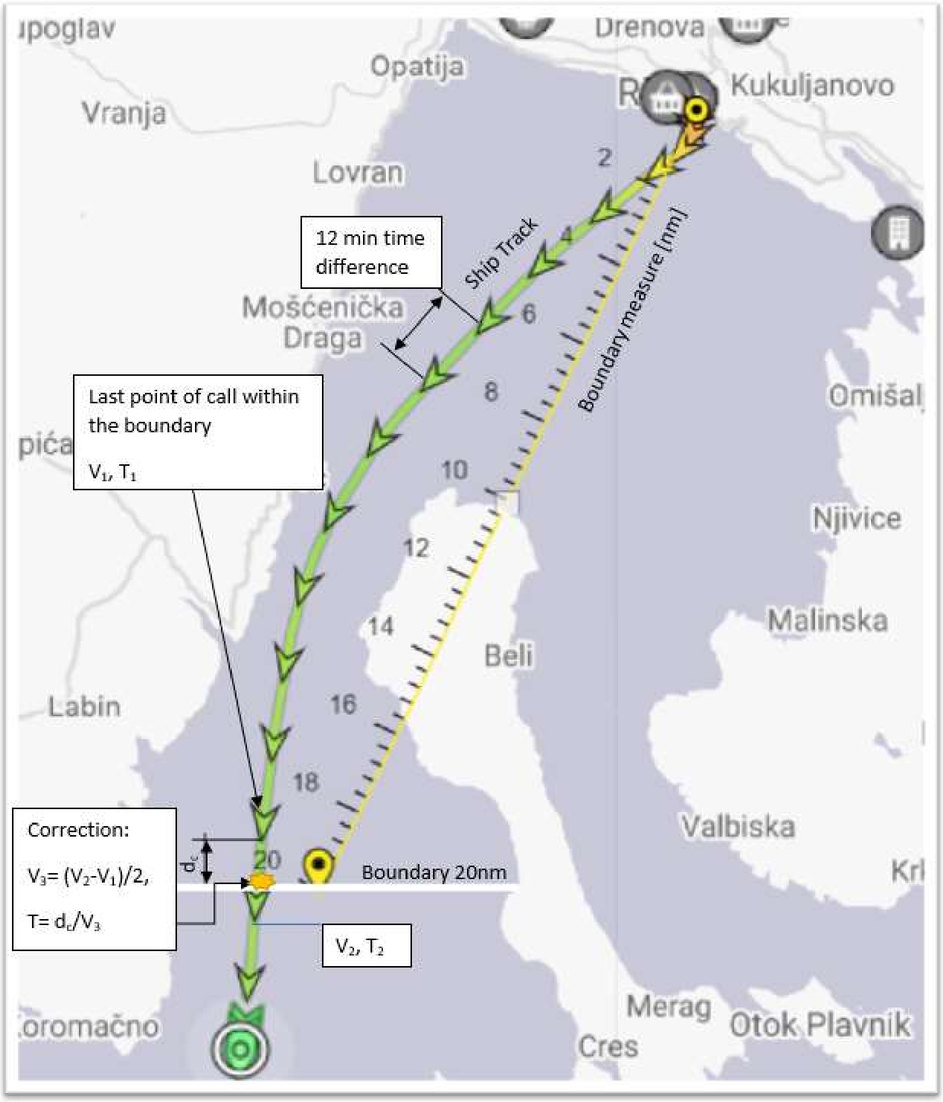

Figure 3. 3: Boundary conditions – correction of distance

For example, if the maximum allowed time between two calls (temporal resolution) was set to 12 minutes, the maximum possible undetected cruising distance is calculated in Equation 3.2. That distance is named D_{max_error}.

$$D_{max\_error} = V_{cruising} \times 0.2\ h \tag{3.2}$$

To reduce gaps in data caused by low temporal resolution, an additional check was introduced that controls the distance between the first detected ship's position within the boundary and the boundary itself. An approximated point of call was set on the intersection of the boundary and shortest distance between two consecutive AIS points. The speed between the boundary and the first AIS point is calculated as an average speed between two consecutive points, and time is calculated using the d/V equation, where speed is assumed constant.

3.4.4 Steps IV and V: Ship activity phases allocation and time

The main engine, auxiliary engines, and boilers will undergo different loads on a ship during the various shipping operations. The bottom-up model simplifies those operations to cruising, manoeuvring, and berthing phases. During the cruising phase, it is assumed that the ship's main engine is used for propulsion, while auxiliary engines are used for hotelling; during the manoeuvring phase, ships use both auxiliary and main engines, where the auxiliary is used for hoteling and the main engine for propulsion only. The ship applies an auxiliary engine for supporting services and port operations during the berth phase. Additionally, the anchorage phase is identified in ports that have such options. During the anchorage phase, as during the berth phase, the main engine is considered not to be in operation, while auxiliary engines provide power for hoteling.

At a temporal resolution of one hour, the example in Figure 3.4 is presented to demonstrate one ship's voyage to the port. Figure 3.4 presents the sequence of the input data to the Bottom-up model, in which each column presents one AIS data record containing data for latitude, longitude and speed. The boundary condition explained in Section 3.4.3 selects data records located within the set boundary. Ship activity is detected as explained in Section 3.2. The three activity phases are marked in different colours: yellow for cruising, green for manoeuvring and white for berthing.

Input from AIS			Ship Activity Phase	Distance
Latitude	Longitude	Speed [kn]		
44.862	14.148	10.5	Cruise	0.00
45.045	14.221	10.8	Cruise	9.05
45.189	14.284	10.6	Cruise	9.28
45.297	14.441	7.9	Manoevre	1.45
45.319	14.455	0	Berth	0.00
45.319	14.455	0	Berth	0.00
45.319	14.455	0	Berth	0.00
45.319	14.455	0	Berth	0.00
45.319	14.455	0	Berth	0.00
45.319	14.455	0	Berth	0.00
45.319	14.455	0	Berth	1.48
45.301	14.431	2.7	Manoevre	3.59
45.249	14.389	6.3	Manoevre	4.30
45.197	14.319	6.7	Manoevre	7.88
45.076	14.247	9.2	Cruise	11.35
44.895	14.17	10	Cruise	0.00

Boundary condition

Figure 3.4: Ship activity phases allocation based on ships' speed

Distance is only calculated if longitude and latitude are within the boundary. Data is not excluded to save processing time and enable the reuse of data to estimate emissions for different research boundary sizes (for example, 10, 15 and 20nm distance to port). A comparison of emissions for different boundary sizes was needed in the research testing, and the validation phase is explained further in Chapter 5. The boundary condition algorithm sets the distance between the points outside the boundary to zero. Once the distance is set to zero, this data row is not considered by the algorithm.

3.4.5 Step VI: Emission factor conditions

Emission factors are assigned according to the year in which the ship was built and the ship's engine power. Emission factors used for CO_2 in this Thesis were defined by the Third IMO GHG study (Smith et al., 2014). The emission factors for SO_X were set according to the IMO legally defined SO_X limits (Smith et al., 2014). For NO_X, it was assumed that ships produce the maximum allowed emission values defined by the IMO NO_X regulations, and levels depend on the ship's engine year of build, engine power and technical emission abatement measures installed (Smith et al., 2014). Ship technical characteristics and installed abatement measures were retrieved through Clarkson's Research portal. Depending on the power of the main engine, emission factors for auxiliary engines and boilers were approximated for different ship activity phases using the statistical averages from the Third IMO GHG study (Smith et al., 2014).

The bottom-up model is used for the validation of the novel SEA methodology. The same emission factors were used in both models so that the two methods of estimating emissions could be compared.

3.4.6 Step VII: Engine load

Ship engine working load is the percentage of the maximum continuous rated power that the ship uses at a given time. The engine load needs to be estimated using the available data, which is ship speed over ground, ship technical characteristics, engine power and engine maximum continuous rated speed, V_{MCR}. Some methodologies consider external weather and sea conditions, the resistance of the ship hull and other parameters, to improve estimation accuracy (Goldsworthy, 2017; Olmer et al., 2017; Jalkanen et al., 2012). This Thesis neglects the external conditions to simplify the process and to prioritise rapid estimation of emissions from numerous ships in ports and coastal waters, which is done for both models so that the results would be comparable.

The vessel-based bottom-up model calculates the main engine load factor during cruising as a ratio of the actual speed over ground V and V_{MCR}, Equation 3.3

Engine Load $LF = (V/V_{MCR})^n$ *(3.3)*

V – ship speed

V_{MCR} – ship's speed at MCR

n – the power of propeller's law

Equation 3.3 is derived from the propeller law. The propeller law states that 'the necessary power delivered to the propeller is proportional to the ship's speed (V) to the power of three'(MAN Diesel & Turbo, 2013). However, measurements show that *n* for medium-sized and medium-speed containerships like feeders and reefers is: *n*=3.5 (MAN Diesel and Turbo, 2013). This value for *n* was used as the average value for container vessels of all sizes. It is to be expected that the value of n will differ for different ship types in relation to ships block coefficient and hull shape.

The method to estimate engine load is presented as a part of the model in Figure 3.1 (step VII).

3.4.7 Step VIII: Ship energy demand

The ship's energy demand is estimated for the main engine, auxiliary engines and boilers. The assumption is made that the main engine represents the only power source for the ship's propulsion. The power demands and EFs of auxiliary engines and boilers are acquired from statistics for containerships, which relate ship installed main engine power and ship capacity in TEU to auxiliary engine power and auxiliary engine power demand in different activity phases (Smith et al., 2014).

Time spent in cruising and manoeuvring activities and ship speed are the primary drivers of the energy demand, while during anchoring and port operation in dock activities, time-efficiency drives energy demand reduction. The main engine is assumed to be inactive in the berth and anchor activity phases, while auxiliary engines provide main hoteling power during that period. In the anchor stage, it is assumed that ships use the same energy as at berth. The anchor stage is detected when the ship has a speed under 1.5 knots, allowing slight lateral movement of the ship. In this model, the time spent in the anchor stage is added to berth phase time.

3.5 Summary of Chapter 3

This chapter presents the Bottom-up model, which implements the (IMO 2014) method. The Bottom-up model was developed to analyse how ship emissions are related to other ship technical and voyage related parameters; for example, how the ship's speed was linked to the ship engine load, which determines the ship fuel consumption. Ship emissions directly linked with ship fuel consumption, CO_2 and SO_X were estimated using the IMO 2014 legally permitted ship emission factors. The quantities of NO_X were estimated based on emission factors which were defined by the IMO NO_X regulations. Therefore, ships were checked for technical characteristics using Clarkson’s Research portal. The bottom-up model provides the emission estimation tool for vessel-based detailed emission estimates.

The development of the Bottom-up model enabled a comparison of this conventional way of estimating emissions and the newly developed SEA methodology, which is further presented in Chapters 4 and 5. The Bottom-up model is used to establish a database of emission estimates for ships' samples in different locations, which is needed to test and validate the SEA methodology.

Chapter 4. The Ship Emission Assessment Method

4.1 Introduction to Chapter 4

The novel methodology for Ship Emission Assessment (SEA) is presented in this Chapter.

The SEA methodology enables the estimation of ship exhaust emissions for ships operating in defined geographic areas. The SEA method combines top-down voyage data and the bottom-up approach acquiring technical ship data to identify ship activity data for emission estimation in defined regional areas and ports. The SEA methodology reduces the cost of data acquisition (Section 4.5.7) and the time required (Section 4.6) to estimate ship emissions. It is proven to have results comparable to the detailed bottom-up vessel-based methodology (verification of the SEA methodology is presented in Chapter 5).

The SEA methodology presents results in grams of pollutant per volume of cargo, specifically TEU for the containership example. The SEA methodology provides a simple to use tool for ports intending to develop or improve their ship emissions assessments to comply with the State emission control strategy (GEF-UNDP-IMO GloMEEP Project and IAPH, 2018).

The SEA methodology provides results that can compare emissions per volume of cargo for different ports or regions. Comparing ship exhaust emissions for a specific region or port helps to understand the efficiency of technical and managerial measures applied in those areas. This comparison of port emission reduction efficiency could lead to a better understanding of the effectiveness of local policy and emission measures.

The SEA methodology quantifies ship exhaust emissions for CO_2, SO_X and NO_X and explores the presentation of CO_2 emissions on the spatial map in this chapter.

4.2 The Ship Emissions Assessment Method (SEA) explained

The SEA methodology fills the gap identified in Chapter 2 between the top-down and bottom-up methodologies for ship exhaust emissions estimates. Key characteristics of current methodologies can be summarised as follows:

1) Top-down methodologies provide rapid emission estimates, which are not accurate enough to provide evidence about local and regional CO_2, SO_x or NO_x emissions from ships (in ports, city areas, river estuaries or, for example, seas with coastlines shared by different states) that would be required for informed regulation and policy management.
2) Bottom-up methodologies are detailed and accurate; however, they are resource-demanding and costly in terms of data and time. The bottom-up methodologies do not provide fast, affordable solutions which could be applied globally in developing countries or ports with limited budgets.

A quick and accurate method to assess emissions from ships in ports and defined areas is now required to assess emissions regulations' effectiveness and provide a tool for future regulations modelling. The method should be accurate as bottom-up estimates while enabling a quick processing time comparable to top-down estimates.

The SEA methodology occupies the space between the top-down and bottom-up methodologies by providing a hybrid solution to quantify CO_2, SO_X and NO_X exhaust emissions from ships using diesel engines and presenting the results as the overall mass of pollutant (tonnes) and mass of pollutant (tonnes) per volume of cargo transported, (in the case of containerships in TEU).

Figure 4.1 illustrates the SEA method process boundary and data sources in the wider process. Key elements of Top-down and bottom-up methods and a hybrid combination of key elements used by the SEA methodology are illustrated.

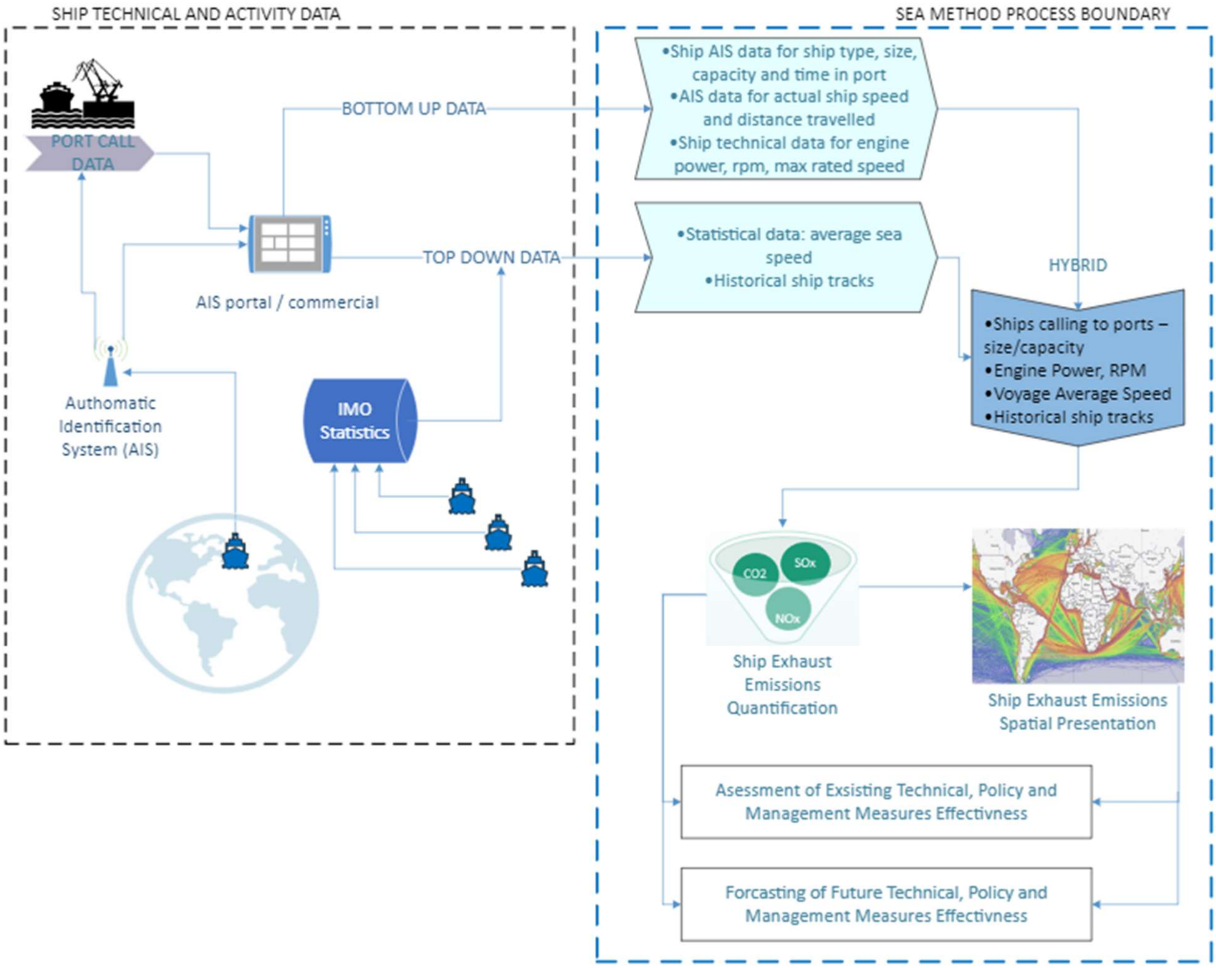

Figure 4.1: Key elements of the SEA methodology and its data sources

4.2.1 The novel Ship Emissions Assessment-SEA methodology flow diagram

The SEA methodology is presented as a hybrid between the top-down and bottom-up vessel-based approach to ship emission estimate. The SEA methodology uses the elements of the top-down method to improve the practicality and speed of the bottom-up method while retaining the ability of the bottom-up to estimate emissions in defined geographic areas around ports and in coastal regions. The functionality of the SEA methodology is explained in the flow diagram, which is presented in Figure 4.2. The flow diagram is divided into three sections signifying top-down, bottom-up and hybrid elements, which are marked with dash and dash-dot line border lines.

The bottom-up part of the methodology is primarily the input part of the process, which considers vessel-based technical characteristics, the selective process for assigning the regulatory emission levels (emission factors based on legal requirements) and the input of voyage data for individual ships. The SEA methodology reduces the need for massive conventional bottom-up AIS datasets and uses an innovative approach to establish ship voyage information. The SEA methodology improves the practicality of the bottom-up data input by application of the recently available data sets, which are used as a proxy for the ship's actual speed and distance travelled through a designated geographical area. The datasets applied provide average values for ship speed, based on the last ship voyage, which is explained further in section 4.5.3. The distance that ships travel is established using the top-down approach.

Top-down elements of the methodology are within the green dotted frame, Figure 4.2. Top-down elements comprise average data obtained from IMO statistical datasets. Additionally, the SEA methodology contributes to the top-down data acquisition approach with the application of historical ship track density maps, which are publicly available at a very low cost compared to historical AIS data.

The innovative application of historical ship density maps is explained further in section 4.5.7.

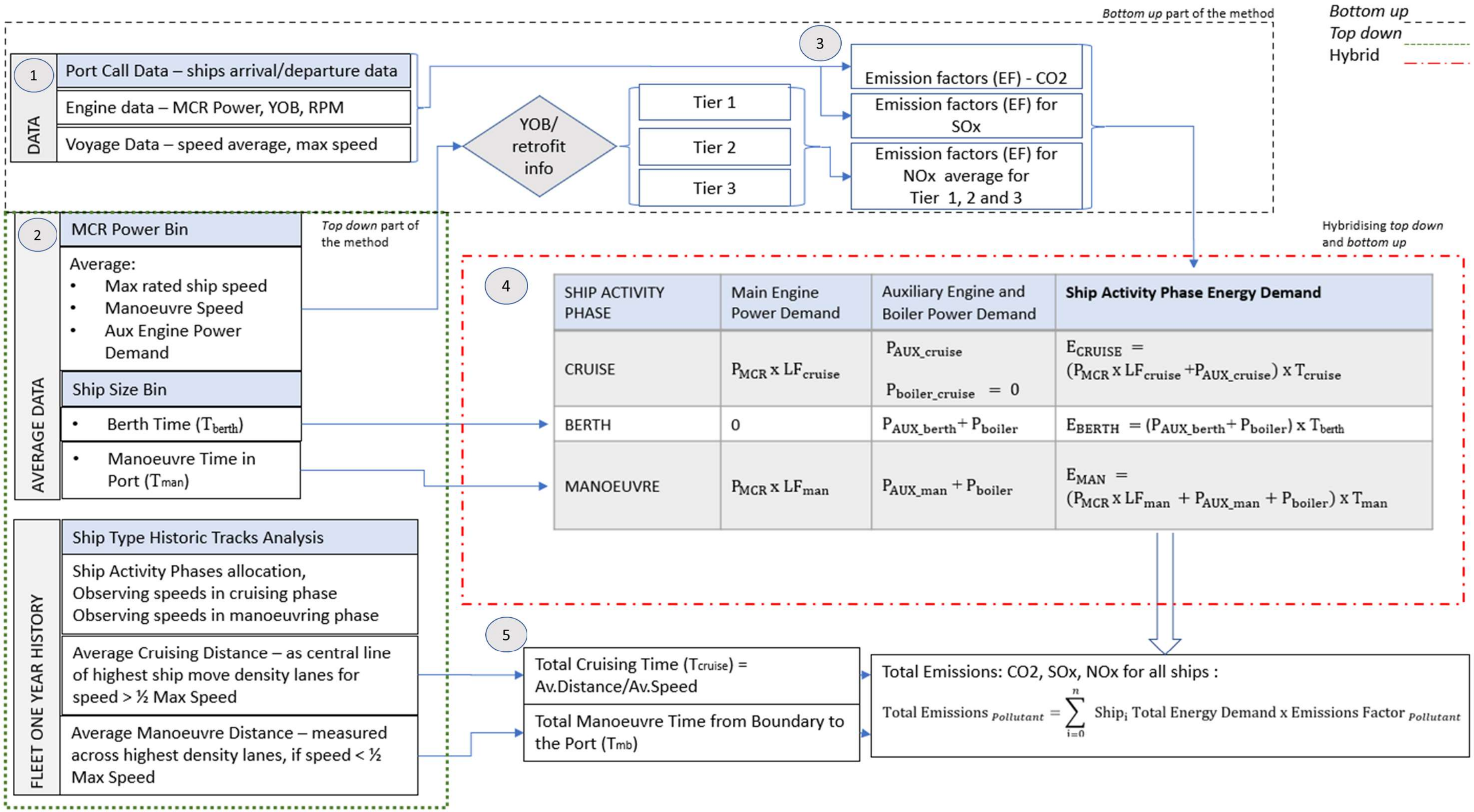

Figure 4. 2: Ship Emissions Assessment-SEA methodology flow diagram

The SEA Method is comprised of 5 key steps, marked by number in Figure 4.2, and explained bellow:

1) Bottom-up data acquisition

The first step of the SEA method that relates to bottom-up methodologies is data acquisition, processing and input of ship technical details (MCR, RPM, ship cargo capacity or volume). This data is acquired through commercial portals, which is explained in Section 4.5. Detail of this from the SEA method diagram (Figure 4.2) is presented in Figure 4.3.

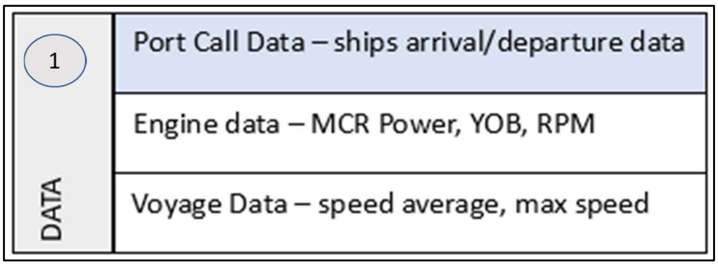

Figure 4.3: First key step of the SEA method is Data acquisition

The obtained technical data is used for the conditional allocation of appropriate regulatory emission factors. The Tier 1, 2 or 3 emission limits for NO_X are allocated according to the year of build of the ship, its engine power and RPM. Those factors are further presented in Section 4.3. Emission factors for CO_2 and SO_X are allocated according to the regulatory measures for main engine power and RPM, as presented in Sections 4.3.3 and 4.3.4.

2) Average Data acquisition

The second part of the SEA method is consisting of average data acquisition. Ship data from key step 1 is sorted by ship size. In the case of containerships, size unit used was maximal number of containership (TEU). If the SEA method is applied to different type of ship, size could be measures in gross tonnes, tank capacity or engine power, according to IMO ship classification (Smith et al., 2014). Average data for different ship sizes is obtained as presented in Figure 4.4.

Berth time is obtained from Port Call Dataset, for individual ships. This data is not relevant in ports that provide shore side electricity from renewable sources.

Manoeuvre time in port is obtained as explained further in Section 4.5.6.

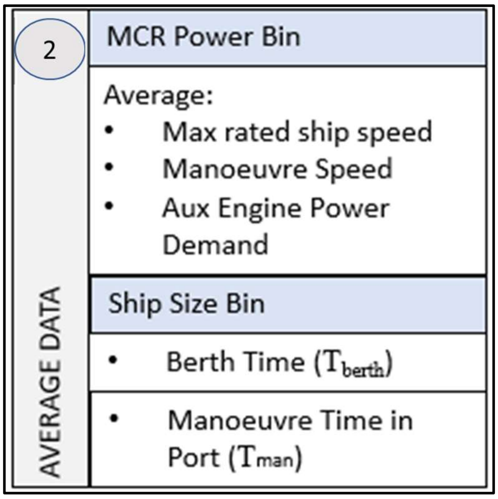

Figure 4.4: Detail of the SEA methodology diagram (Figure 4.2)

Main assumptions

The part of the SEA methodology that relates to top-down methodologies is based on assumptions, which use average data as presented in the detail of the SEA method diagram (Figure 4.4). Assumptions are further explained in Section 4.5.3. and validated in Chapter 5.

3) Application of emission factors

In the key step 3 obtained year of built of individual ships is used to assign IMO NO_X Tier 1, 2 or 3 factors, which is further used to determine the NO_X emission levels. The selection and application of emission factors to obtain total emissions per pollutant from ship exhaust are explained in Sections 4.3.2, 4.3.3 and 4.3.4. The equation from the SEA methodology presented in Equation 4.1 and Figure 4.2 estimates the total quantity of specific pollutants emitted for all ships assessed.

4) Energy demand estimate

Ship energy demand is estimated for different ship activity phases for main and auxiliary engines. Energy demand in each phase is added together to obtain the total energy for each ship voyage assessed. This is explained in Sections 4.5.5 and 4.5.6 and presented in Figure 4.5.

SHIP ACTIVITY PHASE	Main Engine Power Demand	Auxiliary Engine and Boiler Power Demand	**Ship Activity Phase Energy Demand**
CRUISE	P_{MCR} x LF_{cruise}	P_{AUX_cruise} $P_{boiler\_cruise} = 0$	E_{CRUISE} = (P_{MCR} x LF_{cruise} +P_{AUX_cruise}) x T_{cruise}
BERTH	0	P_{AUX_berth}+ P_{boiler}	E_{BERTH} = (P_{AUX_berth}+ P_{boiler}) x T_{berth}
MANOEUVRE	P_{MCR} x LF_{man}	P_{AUX_man} + P_{boiler}	E_{MAN} = (P_{MCR} x LF_{man} + P_{AUX_man}+ P_{boiler}) x T_{man}

Figure 4.5: Ship Activity Phase Energy demand, part of the SEA methodology diagram

5) Total Emissions of CO_2, SO_X and NO_X estimate

Total Emissions: CO_2, SO_X, NO_X for all ships:

$$Total\ Emissions_{Pollutant} = \sum_{i=0}^{n} \text{Total Energy Demand Ship}_i \text{ x Emissions Factor}_{\text{Pollutant}} \quad (4.1)$$

Emissions are quantified using the expression explained in Figure 4.6. A case study for three ports is assessed for CO_2, SO_X and NO_X emissions from containerships, which is presented in Chapter 5.

4.3 Choice of emission factors

The IMO regulatory NOx emission limit requirements apply to all ship sizes and types of ships with diesel engines of installed output power over 130kW. Different levels will apply depending on the ship's year of build (YOB), as different Tiers of NOx levels of emissions were in force when those engines were built. Ships built before January 1st, 2000, comply with Tier 1 levels, which are 80% higher in NOx emissions than Tier III levels of ships built after 2016. The end of life of ships built before 2016 can span throughout the next 20 or more years, which is why it is essential for ports to quantify emissions, differentiate which ships generate the most emissions and understand how to mitigate pollution from ships and how to stimulate stakeholders to reduce emissions.

Application of regulatory emission factors to ships selected by engine power, rpm, and year of build shows quantities of emissions generated in the case where all ships comply with the regulation. The limitation of this approach is that it is not considering changes in NOx emissions in operation under low load, which can only be established by measurements onboard or specific vessel-based modelling. Such a level of accuracy in ship emission estimation is an effective tool to assess the effectiveness of technical abatement measures on board. However, the SEA methodology aims to provide evidence to improve policy and management measures, for which small variabilities in NOx levels are not crucial. The priority of the SEA methodology was to rapidly assess emissions and deliver efficient and comparable estimates of emissions. For this purpose, IMO regulatory emission factors were chosen to reflect how emission regulations impact emission quantities. IMO NOx Tier regulations, which define maximally allowed emissions for marine engines and therefore emission limits, were explained in Section 2.4 and presented in Table 4.1.

These factors were used for all fuels and all engine types. Engine types were conventional diesel engines and diesel-electric, while LNG and alternative fuels did not appear in the researched sample of 1350 containerships at the case study ports (310 containerships in the port of Rijeka, 664 in the port of Venice and 376 in the Port of Trieste).

Energy-based emission limits for NO_X are presented in Table 4.1. The emissions factors for CO2 and SOx were defined in IMO, Marpol Annex VI, Regulation 13 (Marpol, 2017) and presented in Tables 4.2 and 4.3, respectively.

Tier	**Area**	**Standard valid from ship YOB on and after**	**Total weighted cycle emission limit (g/kWh)** **n = engine's rated speed (RPM)**		
			n < 130	n = 130 - 1999	n >= 2000
I	Global	2000	17.0	$45 * n^{-0.2}$	9.8
II	Global	2011	14.4	$44 * n^{-0.23}$	7.7
III	ECA	2016	3.4	$9 * n^{-0.2}$	2.0

Table 4. 1: Energy-based emission limits for NOx (Marpol, 2017)

Emission factors for CO_2 depend on the fuel consumption and therefore vary for different ship activity phases. Emission factors were specified according to the engine type. Standard engine types considered by the IMO Third and Fourth GHG Studies (Smith et al., 2014; 2020) include slow-speed Diesel (SSD), medium-speed diesel (MSD), high-speed diesel (HSD), steam and gas turbines, and different types of LNG fuelled Diesel Cycled engines. However, this Thesis case study is oriented to containerships, and in the sample of over 1000 ships, all engine types were either SSD or MSD. Ships using diesel engines are classed as SSD if their speed in revolutions per minute (RPM) is less than 300, medium-speed diesel if RPM is between 300 and 900, and HSD for all ships over 900 RPM.

Emissions factors for CO_2 are presented in Table 4.2.

g/kWh	MSD	SSD	SEA SPEED
MAIN ENGINE	658	593	CRUISING and MANOEUVRING SPEED
AUXILIARY ENGINE	607	670	ANCHOR
AUXILIARY ENGINE	707	658	BERTH

Table 4. 2: Emission factors for CO2 (Smith et al., 2014; Faber et al., 2020)

This Thesis assumes identical emission factors for auxiliary engines and auxiliary boilers, which are referred to as auxiliary machinery or engine, as was assumed in the IMO (2014) study. Regulatory emission levels for SO_X have changed during the course of this research, from January 1st, 2020, with the IMO Sulphur Cap on the allowed content of sulphur in fuel. Outside the designated sulphur control emission areas (SECA), ships are allowed 0.5% of sulphur in fuel (mass by mass), as explained in Section 2.6. In European ports and SECAs, the allowed percentage is less than 0.1% of sulphur content. The researched case study areas included three EU ports and applied emission levels reflect those regulations.

Emissions factors for SO_X are presented in Table 4.3.

g/kWh	MSD	SSD	SEA SPEED
MAIN ENGINE	1.41	0.37	CRUISING and MANOEUVRING SPEED
AUXILIARY ENGINE	1.41	0.37	ANCHOR
AUXILIARY ENGINE	1.41	0.37	BERTH

Table 4. 3: Emission factors SOx (Faber et al., 2020)

4.4 Ship power demand estimation

Since fuel consumption and ship main engine power demand were unavailable in the public domain, both needed to be estimated based on known parameters.

The key parameter obtained by the AIS system is ship speed. The ship's speed can be used to estimate the engine power. To simplify the process, the main engine was assumed to be the only engine used for propulsion, while auxiliary engines are used for hoteling and port operation energy demand. The load factor was obtained as a speed ratio to the maximum rated ship's speed to the power of 'n', where 'n' is determined by the engine producer (MAN Diesel & Turbo, 2013). The main engine load calculation is explained further in section 4.5.6.

Main engine load is the parameter that has the highest impact on emissions levels compared to other contributors. However, auxiliary engines which are at a low load during the cruising phase contribute to overall ship power demand. Auxiliary engines provide power for hoteling during the anchorage phase and port operation and hoteling during the berth phase. The auxiliary engine load was assumed using statistical averages for specific ship engine power ranges, which vary for ship activity phases. Auxiliary engine and boiler hourly power demands in different activity phases are estimated using the IMO (2014; 2020) population statistics for ship type and capacity size. The time spent in berth, at anchor or manoeuvring is estimated using the SEA methodology approach. Energy used in kWh will be proportional to power demand and time spent in the activity.

The main engine load estimates based on ship actual speed depend on AIS data accessibility and temporal resolution, impacting the load factor estimation success rate in bottom-up models. The SEA methodology, which averages one year of ship activity, could be applied in areas with inconsistent AIS temporal resolution. However, the SEA method extracts ship moves from one year of historical trajectories and uses the proxy for the speed ratio (Equation 4.9, Section 4.5.6) obtained from the average voyage and sea-going speeds to obtain the most probable shipping route and average speed. Hence the SEA methodology bridges the acquisition of the ship location and actual speed over ground and can be used when AIS data cannot be obtained for individual vessels or ships in the designated geographical areas.

The novelty of the SEA method is the estimation of the energy demand of ship traffic using the historic ship tracks and statistical data on port arrivals and departures. This approach bridges bottom-up vessel-by-vessel estimation and produces accurate aggregated energy demand estimates. The SEA method identifies the most probable shipping route by following the visual line of the highest density of the historic ship moves, which improves the certainty of results in situations where other bottom-up methodologies cannot operate due to low temporal resolution or high 'noise' in AIS data.

Data acquisition describes single ship voyage data estimates from ship density maps, which is explained further in the next section. The methodology reveals patterns in ship activity, which can be compared to traffic lanes. Additionally, the estimation of time in each activity is the novelty presented in Section 4.5.4 and further explained in the case studies in Chapter 6.

4.5 Data acquisition

4.5.1 Port calls data

The port calls dataset can be obtained directly from the port or commercial AIS portals, e.g. Clarkson's Research or Marine Traffic. Ships need to be classified by ship type as each ship type needs independent input to the SEA methodology computational model.

Port calls data includes:

1) ship times of arrival and departure at/from port
2) time in berth
3) the ship name and IMO number
4) ship cargo capacity (in the case of the containership, it is a maximum capacity, TEU)

Ship times of arrival at and departure from the port are different from when the ship has entered the designated port boundary assigned as an input to the SEA methodology.

4.5.2 Engine Data

Engine specific information is obtained from Clarkson's Research portal alongside Year of Build (YoB) and retrofits information. The categorisation of the ships is done by the algorithm of the SEA methodology, which assigns ships with appropriate emission factors depending on ship activity phase and considering IMO NOx regulative emission levels, as explained in sections 4.3.2 to 4.3.5.

Engine data includes:

1) year of build (YoB) and retrofit information (SO_x or NO_x scrubber)
2) installed main engine power (MCR)
3) revolutions per minute (RPM)

4.5.3 Voyage data

Datasets describing ship voyages were applied to save time in estimating a ship's average cruising distance. This Thesis research explored different sets of data previously not applied in ship emission estimates to optimise costs and the need for historical data. The selected datasets applied in the SEA method significantly reduce the cost of data acquisition compared to historical data obtained for bottom-up methodologies.

Ship voyage data, which amongst other information, lists voyage average and maximum speed and voyage length, has become a standard inclusion in datasets listing ships calling at the port, known as port calls (ships arrival and departure) data. Voyage speed average ($V_{voyage-average}$) is an individual ship's average speed between the last two ports.

Average sea speed and average maximum rated speed are obtained from statistics on the world containership population (Smith et al., 2014). These values are accessible from averaged empirical data in IMO statistics by ship types.

Voyage data includes:

1) voyage speed average ($\mathrm{V}_{\mathrm{voyage-averag}}$)
2) averaged sea speed for containership capacity size bins ($\mathrm{V}_{\mathrm{Sea\ Speed\ Average}}$)
3) maximum rated speed (V_{MCR})

The application of voyage data is explained in Section 4.5.7. How voyage data acquisition and application compare to top-down and bottom-up methodologies is explained in more detail in Section 4.5.8, step 1.

4.5.4 Activity data

Twelve months of consecutive ship track density maps for the year 2019 were analysed for ship activity areas, as discussed in Section 4.1, with the below-listed lengths measured along the central line of the ship tracks at the highest density:

1) averaged distance of cruising tracks from entry to exit of the port's boundary
2) average manoeuvring track length within the port's boundary

When the ship is at anchor, it is also assumed that the main engine is turned off while auxiliary engines are running at their sea load, which is determined as presented in section 4.5.6.

4.5.5 Auxiliary engine's power demand

The research scope and uncertainties about using the ship energy demand estimate to establish fuel consumption and subsequential quantities of NO_x, SO_x and CO_2 emissions were discussed in sections 2.5 to 2.7. Assumptions about input data in the first step included the choice of emission factors, as explained in section 4.3.

In further steps, estimation of the engine load assumes the auxiliary engines are at a low load during the cruising phase and at medium load during manoeuvring, and highest load in port. The main engine is assumed to be completely turned off during the ship's time at berth and when the ship is at anchor, while auxiliary engines are running at a high load. The power demand for auxiliary engines and boilers is assumed using statistical average values based on empirical trials for different ship activity phases (Smith et al., 2014).

4.5.6 Energy demand for ship activity phase

The proposed SEA methodology estimates the ship's total energy demand in kWh per voyage. The ship's total energy demand, Equation 4.2, is directly linked to fuel consumption and can be further used to calculate the emissions for individual pollutants, presented in Equation 4.3. Total emissions of CO_2, SO_X or NO_X for all ships are obtained as a sum of each ship's emissions for individual pollutants, presented in Equation (4.4).

$$Ship\ Total\ Energy\ Demand\ E_{TOTAL} = E_{CRUISE} + E_{MAN} + E_{BERTH} + E_{ANCHOR} \quad (4.2)$$

$$Ship\ Emissions\ _{Pollutant} = Ship\ Total\ Energy\ Demand\ x\ EF\ _{Pollutant} \quad (4.3)$$

$$Total\ Emissions\ All\ Ships\ _{Pollutant} = \sum_{i=0}^{n} Ship_i\ Total\ Emissions\ _{Pollutant} \quad (4.4)$$

Ship total energy demand is defined as a sum of energy demands in each ship activity phase during one voyage through the research boundary. This includes ship entry to the boundary, possible waiting for the port operations at anchorage, berth phase, which includes port operations and finally exit from the port and the research boundary. During these activities, ships will manoeuvre as they approach anchorage and berth.

Total emissions are quantified for each pollutant, CO_2, SO_X and NO_X. Ship total energy demand is multiplied by the emission factor for the pollutant to obtain the total emissions of the pollutant considered.

Ship activity is defined by the speed of the ship, as presented in Table 4.4. The SEA method is compared with the IMO *bottom-up* method (IMO 2014) for the ship speed values used to define the activity phases.

Method	*Bottom-up model* *Vessel-based*	*SEA method* *Voyage-based*
Ship Activity Phase	Input: speed over ground	Input: voyage average speed
Berth	0-3kn	0
Manoeuvring	$3kn < V_{sog} < V_{MCR}/2$	$V_{man-average} = 0.3 * V_{Sea\ Speed\ Average}$
Cruising	$V_{sog} > V_{MCR}/2$	$V_{voyage-average}$

Legend:
V_{sog} – speed over ground (obtained from AIS)
$V_{man-average}$ - average manoeuvring speed

Table 4. 4: Ship activity phase allocation using speed over ground (V_{sog}) by the Bottom-up model (Chapter 3), compared to the SEA method using averaged speed values

The SEA method is based on estimates per voyage. For this method, a voyage event is defined as a ship's singular visit to the port. The voyage speed average is input from the voyage dataset, where the distance of the voyage is calculated between the last two ports of call.

Energy demand for each ship activity phase is estimated, for main engines, auxiliary engines and boilers, as presented in Section 2.7; Equation 4.4, Equation 4.5, and Equation 4.6

$$E_{CRUISE} = P_{MCR}\ x\ T_{cruise}\ x\ LF_{cruise} \tag{4.4}$$

$$E_{MAN} = (P_{MCR}\ x\ LF_{man} + P_{AUX\_man} + P_{bolier\_man})\ x\ T_{man} \tag{4.5}$$

$$E_{BERTH/ANCHOR} = (P_{AUX_{berth/anchor}} + P_{bolier_{bert\ \ /anchor}})\ x\ T_{berth/anchor} \tag{4.6}$$

P_{MCR} – main engine maximum rated power
P_{AUX} – auxiliary engine, average power demand for ship activity phase.

P_{boiler} – auxiliary boiler, average power demand for ship activity phase

LF_{man} – the main engine, assumed load factor, per voyage, during the manoeuvring activity

LF_{cruise}– the main engine, assumed load factor, per voyage, during the cruising activity

T_{cruise}– the time a ship spends in the cruising phase

T_{man}– the time a ship spends in the manoeuvring phase

$T_{berth/anchor}$ – the time a ship spends in the port operations at berth or anchor

Engines identified as retrofitted with a catalytic recirculation system for NO_X were considered as Tier III engines.

Time at berth (T_{berth}) is retrieved from port calls data. Coefficient 0.3 is the speed adjustment factor assumed for the manoeuvring phase, as presented in Table 4.4.

Time for cruising (T_{cruise}) is calculated using Equation 4.7.

$$T_{cruise} = \frac{\text{Average Distance}_{cruise}}{V_{voyage-average}} \tag{4.7}$$

Average Cruising Distance is obtained from the Ship Historic Tracks Map, and Voyage Speed Average is obtained from the Voyage Data, as explained in Section 4.5.7.

Time manoeuvring (T_{man}) is calculated using Equation 4.8.

$$T_{man} = \frac{\text{Average Distance}_{man}}{V_{\text{Sea Speed Average}} \text{ x } 0.3} \tag{4.8}$$

There are limited test results available for emissions from engine loads lower than 25 per cent. The experimental study on Tier II containership vessels by McCaffery (2021) states that the main engine power is reduced to 25-30 per cent load during berth entry and exit manoeuvres. Main engine load in the manoeuvring phase LF_{man} is assumed to be 0.3, as this study presents the average main engine load for acceleration and deceleration in the manoeuvring phase.

Main engine load in cruising (LF_{cruise}) activity phase is estimated using Equation 4.9, where “n” for containerships is assumed to be 3.5, as suggested by (MAN Diesel & Turbo, 2013).

$$LF_{cruise} = \left(\frac{V_{Sea\ Speed\ Average}}{V_{MCR}}\right)^{n} \quad (4.9)$$

4.5.7 Acquiring the Voyage Data from Ship Tracks maps

Most merchant ships have route patterns; therefore, it is possible to understand ship movements and the distances of a ship cruising and manoeuvring lanes using one-year ship track maps.

This Section presents how to back-estimate ship activity and time spent in the activity, from readily available ship density maps, through three steps processes.

STEP 1 – PORT CALLS DATA ACQUISITION

As explained in Section 4.5.1, ship port call data is retrieved from a commercial platform or alternative sources (port arrival and departure). , one for each voyage Commercial AIS data portals provide ship AIS historical data and additional statistical voyage information, which is charged per data record and used as a unit for the data price. The data record is the smallest unit of historical data, containing a set of identical data types. For example, one AIS record containing data types: time of the signal, course, location and speed is referred to as 'one data record'. Historical data can be purchased through commercial portals, which is expensive in terms of subscription or one-time dataset purchase. The one-year ship density map can be used to assume ship average routes, and it is inexpensive and readily available through different sources (Marine traffic, 2019).

Historical data for one year of ships calling at the Port of Trieste, from October 2018 to October 2019, was retrieved to demonstrate this data acquisition.

This historical dataset contained 376 containership voyages, which equals 376 data records. These records, along with ship technical data, were used to estimate one year of containership emissions in the 20nm boundary.

Figure 4.6 demonstrates the alphabetically ordered first 19 voyages of 6 different vessels calling at the port of Trieste. The advantage of alphabetical ordering is that it groups the voyages of the same ship within one year. Figure 4.6 shows that the ships Angela and APL Turkey made only one voyage to the port, ships APL California and APL New Jersey made two voyages and the ship AS Carolina made seven voyages to the port of Trieste in 2018-2019. Such groups of voyages by the same ship were selected for the verification method, as explained in Chapter 5.

The term “one voyage” is explained in Figure 4.6 by presenting the data used to define it.

One voyage

	IMO	Name	TEU	YOB	Arrival Time	Departure Time	Time in port (days)
1	9326976	Angela	862	2005	27/05/19 @ 04:58	28/05/19 @ 10:55	1.25
2	9350044	APL California	6,350	2009	01/07/19 @ 02:58	02/07/19 @ 00:57	0.92
3	9350044	APL California	6,350	2009	22/04/19 @ 08:53	22/04/19 @ 22:54	0.58
4	9350020	APL New Jersey	6,350	2008	17/06/19 @ 01:58	17/06/19 @ 23:55	0.91
5	9350020	APL New Jersey	6,350	2008	08/04/19 @ 11:56	09/04/19 @ 02:53	0.62
6	9532771	APL Turkey	6,350	2009	12/08/19 @ 08:55	13/08/19 @ 00:50	0.66
7	9314935	AS Carolina	2,824	2006	13/09/19 @ 04:55	13/09/19 @ 17:56	0.54
8	9314935	AS Carolina	2,824	2006	19/08/19 @ 10:59	21/08/19 @ 01:50	1.62
9	9314935	AS Carolina	2,824	2006	20/07/19 @ 16:57	21/07/19 @ 05:58	0.54
10	9314935	AS Carolina	2,824	2006	21/06/19 @ 20:59	22/06/19 @ 12:51	0.66
11	9314935	AS Carolina	2,824	2006	21/[illegible]	21/05/19 @ 19:59	0.63
12	9314935	AS Carolina	2,824	2006	18/[illegible]	19/04/19 @ 20:57	1.38
13	9314935	AS Carolina	2,824	2006	22/03/19 @ 16:55	23/03/19 @ 07:57	0.63

One ship

Figure 4.6: Partial data record for one “voyage” for one ship

Data describing each ship’s voyage will be referred to as one AIS signal. This Thesis uses historical AIS data, which is then referred to as an AIS record, while an AIS signal is referred to as a single unit of AIS data obtained instantaneously. The term ‘voyage’ presents the ship’s entire activity from the moment of entry to the designated port boundary throughout its stay and exit from the boundary.

One AIS record for a voyage contains the following types of data:

- Ship IMO number, name and TEU
- Time of entry and exit from the port (arrival time and departure time), as per port record

- Time in port (the difference in timestamp when the ship is first and last ‘seen’ by the port. This time is used just as a control point to eliminate repetitive AIS records.
- Time at berth
- Voyage average speed

The bottom-up methodology (Chapter 3) needs 50 to 500 data records to estimate emissions for a 20nm voyage. The exact number will depend on AIS temporal resolution, ship speed, time at anchorage and time spent in port activity at a berth. However, the SEA methodology applies one voyage data record to estimate emissions from ships engaged in that voyage.

A sample of 75 containership voyages, representing all ship bin sizes, was used to estimate emissions using the SEA methodology and the voyage based, bottom-up methodology (Chapter 3). The voyage-based SEA methodology used 75 voyage data records to estimate total emissions for the selected 75 ships. In contrast, the vessel-based bottom-up methodology used 729 data records to estimate emissions for the selected ships. However, the time resolution was 30min to one hour between the AIS signals, as a higher resolution was unnecessary and required significantly more data. For example, a resolution of 1 minute would require 30 to 60 times more data. The SEA method used $1/10^{th}$ of the data needed for the more detailed bottom-up methodology, with comparable results, as demonstrated in Chapter5. The SEA methodology aims to accurately quantify ships’ emissions in the selected area; however, limitations exist for sample sizes smaller than 20 ships, which is explained in Chapter 5.

STEP 2 – ADDING TECHNICAL SHIP DATA

Ships are assigned with technical information and the main engine power in kW and speed in RPM.

Ships are sorted alphabetically rather than in chronological order, enabling more accessible ship selection and adding of ship technical information.

STEP 3 – ANALYSING SHIP DENSITY MAPS

Ship Historic Tracks, also known as ship density maps, are analysed within the research boundary, which was set to 20nm from the containership berth, as explained in Chapter 1.

Traffic lanes with the highest density of containership moves per square kilometre were identified. Vessels using lanes were then analysed to understand patterns in containership navigation and ship activity phase locations along the lanes.

The shipping lane selection is based on selecting the route with the highest density of ship moves. Consequentially, the selected route is the route of the highest probability for the observed year. The SEA method assumes that the probability of ships taking the same route in the same area will not change in the first consecutive year.

Taking the Port of Trieste as an example, two lanes were identified and measured along the central line of highest congestion, as shown in Figure 4 .7 and Figure 4.8. The two lanes presented in the figures are used for port entry and port exit Port entry and exit routes were added together to obtain the total distance of a shipping route within the boundary.

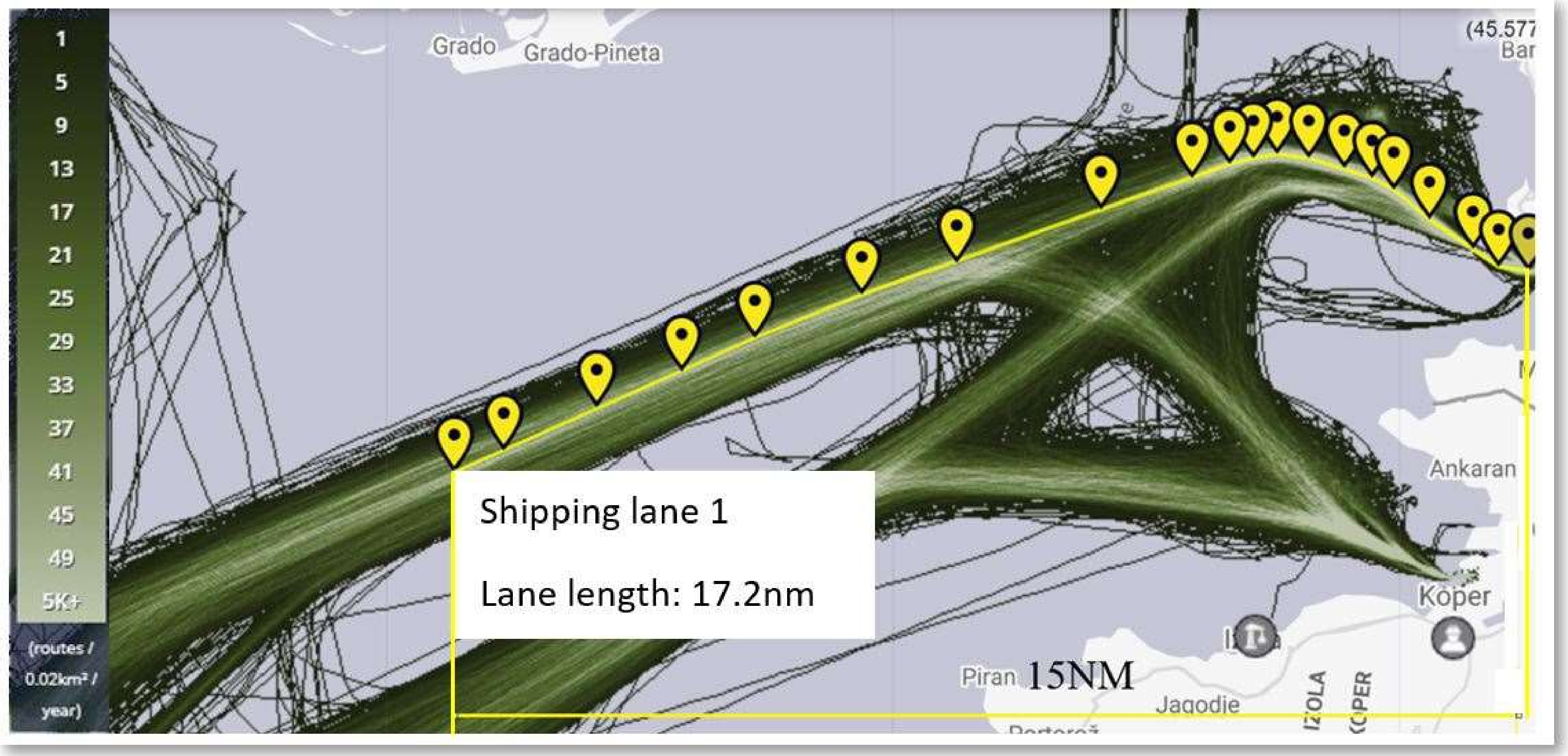

Figure 4.7: Shipping Lane 1, 17.2nm average length (Marine Traffic, 2020)

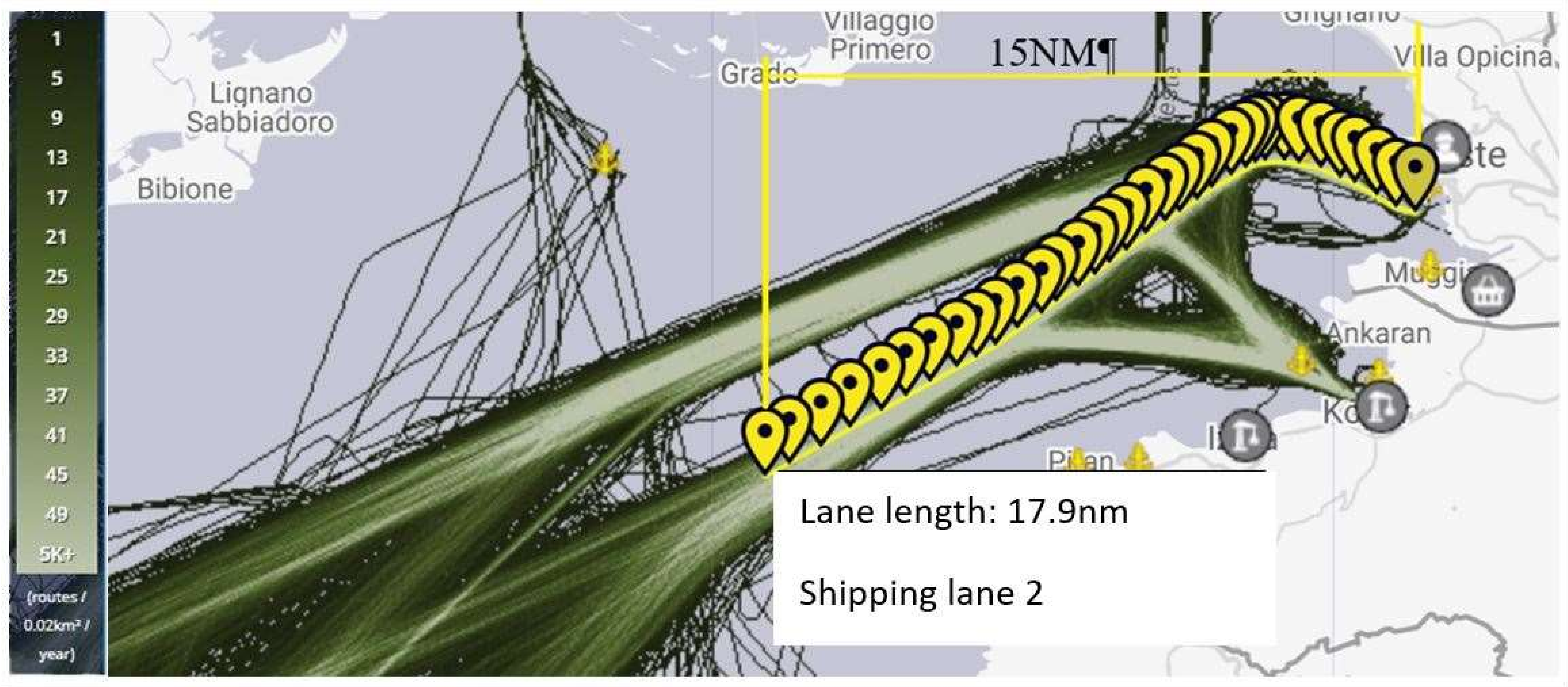

Figure 4.8: Container ships shipping lane 2, length: 17.9nm (Marine Traffic, 2020)

A third shipping route is measured from the boundary edge to the anchorage zone, as illustrated in Figure 4.9. This route is measured to the approximated central point of the anchorage zone.

The anchorage zone is analysed using the spatial map in which ship AIS signals are presented as singular points in the density map, as presented in, Figure 4.10. AIS signal location points are also referred to as 'points of call'.

The SEA methodology detects the ships at anchorage, which is based on port activity observation. The shipping activity in port observation using the real-time AIS monitoring, combined with the port calls data analysis, did not establish any correlation between the waiting time in the port at the anchorage and containership size.

Observation of the researched ship sample and individual past tracks showed that for the example port of Trieste, ships taking more than 24 hours in the port get assigned to use the anchorage. Therefore, the assumption is that ships taking more than 24h in port are assigned to the anchorage. Consequently, the SEA methodology assigns ships taking more than 24hours for the time in port with Lane 3 cruising distance, as it was assumed that those ships were using the anchorage. The ship anchorage assumption needs to be assessed for each particular port

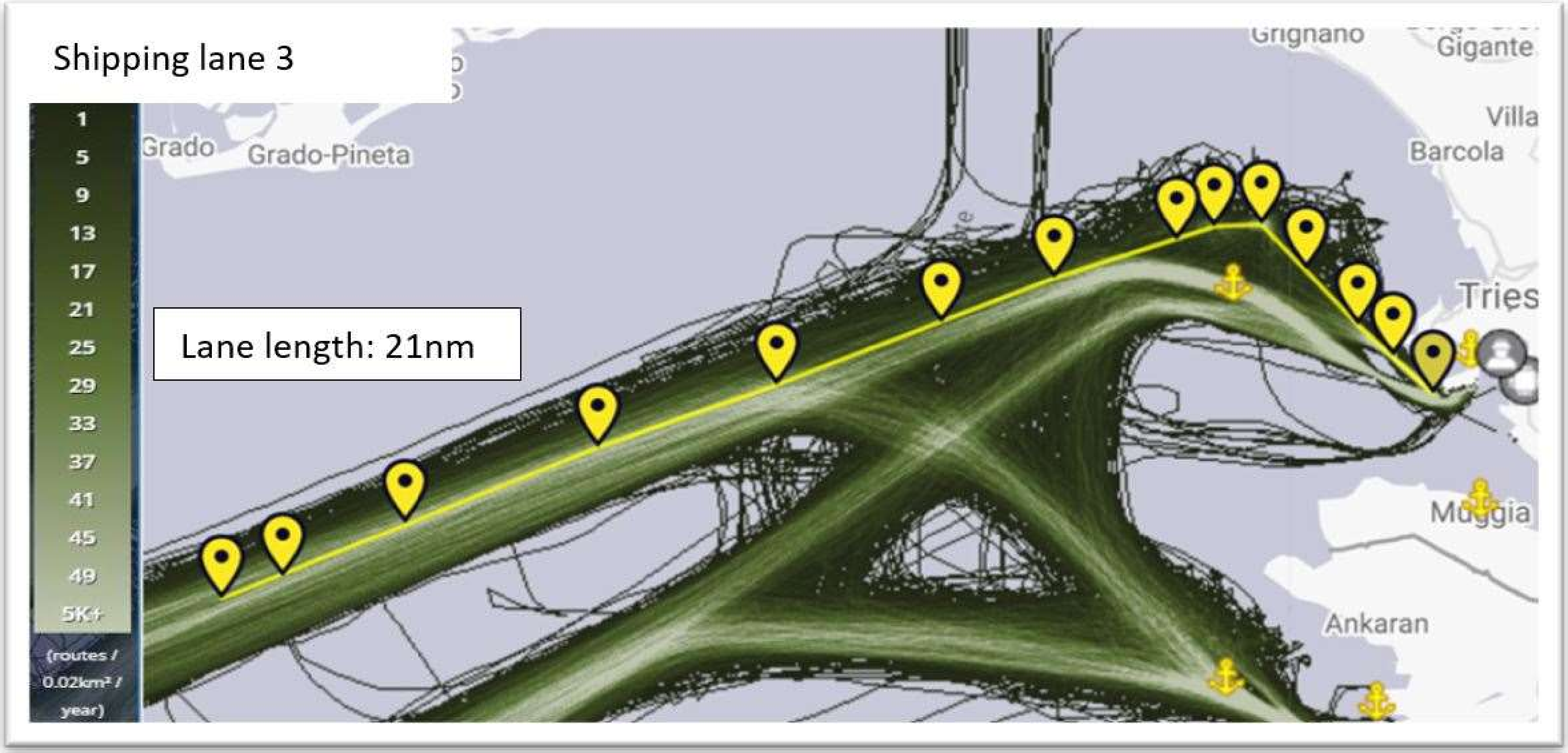

Figure 4.9: Third route leading to the anchorage and further to the port (Marine Traffic, 2020)

Figure 4.10: Ship anchorage locations presented in ship density map by ‘points of call’ (Clarkson’s Research SEA/NET, 2020)

The point where speed becomes less than half of the average sea speed for the area is assumed to be the start of the manoeuvring phase, as explained earlier in Section 4.5.7. Manoeuvring distance is subtracted from the averaged voyage distance to get averaged cruising distance.

4.6 Spatial emission representation

Emissions of CO_2 for one year of containership traffic were estimated using the SEA methodology, as explained previously in this chapter. Aggregated emissions for all containerships were then distributed along the one-year historical containership tracks on a spatial map. The method of distribution of the quantified aggregated emissions along the shipping tracks is explained in this Section.

Standard bottom-up methodologies estimate emissions on a vessel-by-vessel basis, and some bottom-up methodologies present ship tracks on spatial maps. However, on the spatial map, all ship tracks aggregate, and the result is a spatial one-year historical map of ship tracks (also known as a ship density map).

The SEA methodology uses readily available ship density maps to present and quantify emissions and enables '*top-down quick*' and practicable assessments of ship emissions near city and port areas. Hence, the SEA methodology operates at a top-down methods speed with accuracy comparable to the bottom-up method. The advantage of the novel SEA methodology is that it re-calculates existing historic ship tracks and thus enables the top-down time of emission estimates for many ships. Utilising existing historic ship tracks saves costs of historical AIS datasets purchase or data and time for instantaneous AIS data acquisition.

Additionally, the SEA methodology uses ship track density to present emissions from ships spatially – providing a general understanding of where ship emissions are generated.

It can be seen in Figure 4.11 that shipping track density remains similar in the distribution in the whole regional area of the Port of Trieste Bay, therefore providing an estimate of emissions for the port boundary area and the wider region.

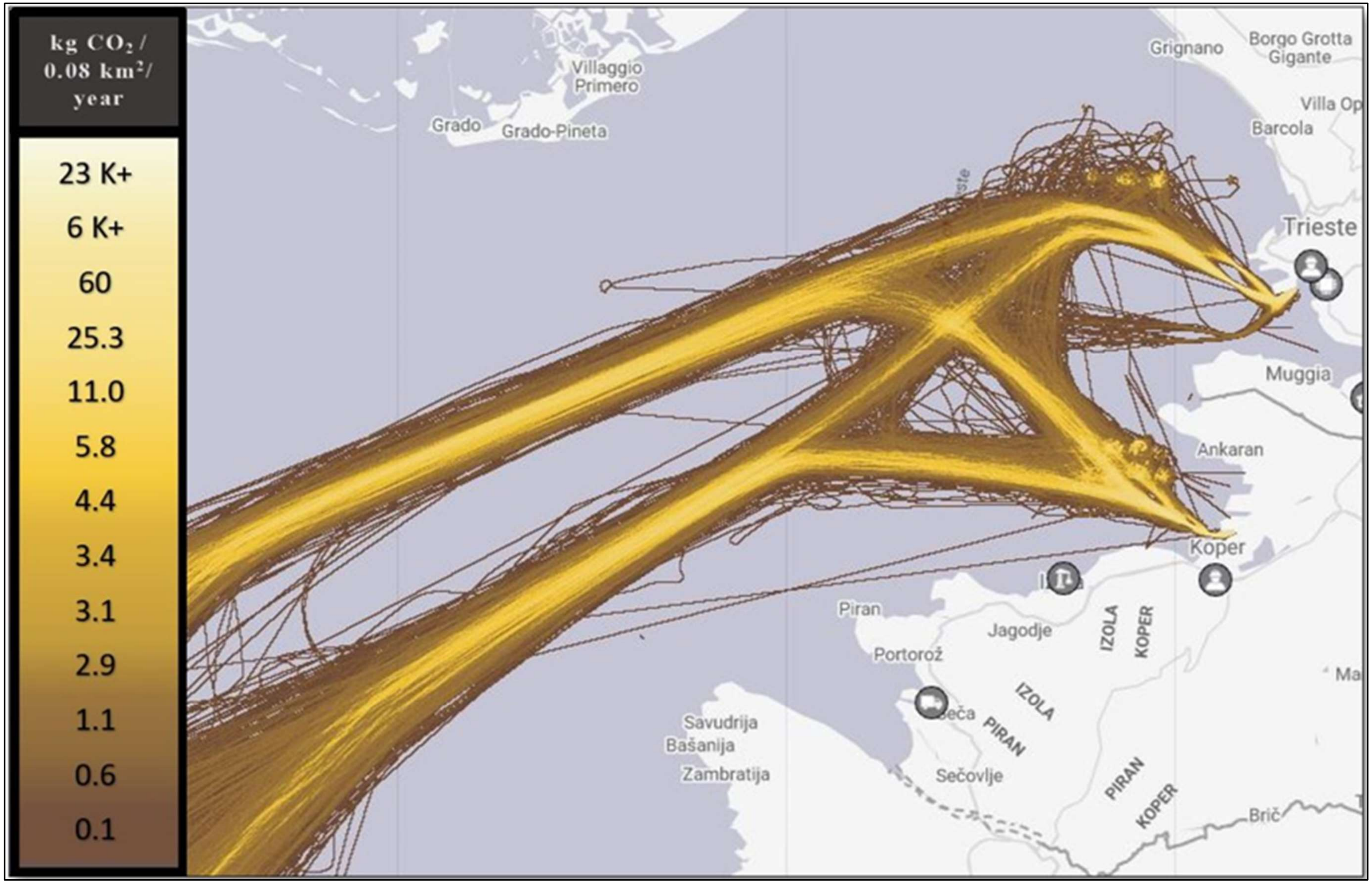

Figure 4.11: CO_2 emissions by containerships in the Port of Trieste in 2019

Ship tracks or routes are divided into a grid of squares of size 0.08 km^2. Table 4.5 presents the number of ship tracks per square kilometre and the distribution of where CO_2 was generated along the shipping tracks [kg/0.08km^2].

Ship tracks/0.08 km^2	***CO_2 [kg/0.08 km^2]***
200 000	22,920
50 000	5,730
521	59.7
221	25.3
96	11.0
51	5.8
38	4.4
30	3.4
27	3.1
25	2.9
10	1.1
5	0.6
1	0.1

Table 4. 5: Conversion table for a spatial map legend, from ship tracks to CO_2 per area

The total quantity of CO_2 emissions is divided by the number of voyages to understand the emission distribution per ship track segment. The assumption is made that each ship track spans the lengths of the grid sides.

Emissions per ship track (obtained in Equation 4.10) are multiplied by the number of tracks in the historic ship tracks legend (Table 4.5) to obtain CO_2 emissions per area [kg/0.08 km^2].

$$\text{Emissions per ship track} = \frac{\text{total emissions (pollutant)}}{\text{number of voyages} * \text{number of tracks in the voyage}} \qquad (4.10)$$

The SEA methodology re-uses existing historical ship density tracks to obtain this spatial emission representation. This is how the SEA methodology reduces the time required to obtain the spatial representation of emissions from ships from the one year of instantaneous AIS data collection or the high costs of acquiring AIS historical data for the entire year of ship activity. The acquisition of the specific ship activity data for the geographic area is complex as ship data is vessel based.

The re-use of the ship tracks in the aggregated spatial map enables rapid spatial emissions presentation, which can be obtained within minutes after the quantification of emissions of CO_2 or SO_X is known.

Due to the complexity of NO_X formation in the combustion process, those emissions cannot be presented as a linear dependency of the average voyage distance, like CO_2 or SO_X, which directly depend on fuel consumption. For emissions of NO_X, the production of emissions could be higher for low engine loads (Jahangiri et al., 2018) but more dependent on the time ships spend manoeuvring and in the port.

4.7 Summary of Chapter 4

The SEA methodology for ship emissions estimates in geographic areas and ports was developed and explained in this chapter. The SEA methodology is more time and data-efficient than the existing ship emissions estimation methodologies. The method is explained, and innovative solutions to reduce data costs and processing time are presented.

The research presented in this chapter demonstrates the new approach to using global ship tracks for ship emissions estimation. Emissions of CO_2, NO_X and SO_X are quantified and explained in a step-by-step process. Finally, the spatial presentation of emissions is explored for CO_2 emissions. The spatial presentation reveals where emissions are happening and the understanding of emission levels of shipping in the area extending outside the boundaries of the assessed geographical area. The obtained quantified results of CO_2, NO_X and SO_X emissions are presented in Chapter 6.

The SEA methodology combines the bottom-up, detailed technical vessel-based data and top-down rapid average values for ship activity and voyage information. This innovative hybrid solution enables the SEA methodology to improve data processing time 10 to 100 times compared to the bottom-up methodology, which is further presented in Chapter 5. Additionally, the SEA method reduces data requirements 50 to 500 times, saving historical data purchasing costs, which is further presented in Chapter 5, Section 5.7. The SEA methodology enables global assessment of shipping emissions in any port, coastal or sea area.

Validation of the SEA methodology is presented in Chapter 5, using the comparison of the results against the bottom-up vessel-based methodology presented in Chapter 4. Further application of the SEA methodology to 3 ports is presented in Chapter 6.

Chapter 5. Validation of the SEA methodology

5.1 Introduction to Chapter 5

The SEA method requires testing to establish the accuracy of its results. It was validated by comparing its results to the vessel-based Bottom-up model, which implements the IMO (2014) methodology, as presented in Chapter 3. The Bottom-up method was applied to estimate vessel CO_2, SO_X and NO_X emissions, using three historical AIS datasets of containership voyages, for 20, 100 and 500 ship voyages, where a voyage represents the time and activities of a ship from the time of entry to time of exiting the researched port boundary area.

The SEA method used top-down ship voyage-based averaged data for the same samples of 20, 100 and 500 containership voyages to estimate CO_2, SO_X and NO_X emissions. The SEA methods' results were compared for the first two samples (20 and 100 ship voyages) to understand the differences between the SEA method results and the more detailed Bottom-up model results. The first ship sample of 20 ships was selected to build a database of emission estimates using the established Bottom-up method. The Bottom-up method emission estimates database was used as a reference during the development of the SEA method. The second sample of 100 ships contained all containership types and sizes within one year of containership traffic to the Port of Rijeka, which was used to show that the SEA method results can be repeated and compared to the Bottom-up method results.

The main estimation parameter for both methods is energy consumption in kWh for each activity, and therefore, the main comparison is on energy consumption between the two methods; hence the same emission factors could be adopted. The total emissions of CO_2, SO_X and NO_X obtained for the samples using the SEA method were compared to the results obtained from the Bottom-up model for the same ships in the designated boundary. For the first two ship samples, the vessel-based emissions obtained by both methods were also compared.

For the third comparison, the SEA methodology was compared to the Bottom-up model, which used averaged emission factors. Hence the same ship voyage AIS record dataset was estimated for emissions using the Bottom-up model, which applies average emission factors for engine power and RPM. Estimates of ship NOx emissions obtained this way were compared to estimates obtained by the SEA method, which considers vessel compliance with IMO NOx Tier regulations. The advantage of applying the SEA method, which assigns regulatory limits of NOx emissions for each vessel, is that its results present the efficiency of the regulatory measures in the reduction of NOx, which is particularly important to evidence in coastal areas outside NECA. The SEA methodology averages ship time in activity and speed but projects an accurate understanding of the readiness of ships in the researched area to mitigate NOx emissions. The SEA results were compared to a more detailed Bottom-up model, which emphasises vessel-based speed and engine load accuracy but does not differentiate ships according to compliance with IMO NOx regulations. The results present the application of the SEA methodology in understanding fleet compliance with NOx standards.

5.2 Method Verification Strategy

Several pathways of the method verification strategy were explored; however, the SEA method comparison to the Bottom-up method proved the best option, which is explained in this section.

The methodology to provide reference data to verify the SEA method results was explored using published emission estimates (ED61406- Issue Number 5, 2017). However, the analysed methodologies in the literature review referred to ship activity older than two years (Pastorčić et al., 2020; Huang et al., 2017; Toscano & Murena, 2019; Goldsworthy, 2017; Olmer et al., 2017; McCaffery et al., 2021). Publicly available historical AIS data has a maximum historical span of one year, making results challenging to compare. The datasets used in journal papers and other published literature are not generally accessible, so the results could not be compared for the same ship voyage data (Smith et al., 2014; ED61406- Issue Number 5, 2017; Merk, 2014a,2014b; Olmer et al., 2017)

The initial method comparison was conducted against a published ship emission port inventory (Williamson et al., 2017); however, assumptions were needed to mitigate changes in shipping intensity and emissions regulations so that emissions from the year 2016 could be compared with emissions three years later in the same port. The comparison with the published results was not adequate to evaluate the accuracy of the results of the SEA method; however, it provided general guidelines in the stage of the SEA method development (comparison with published results is presented in Chapter 6, as an application of the methodology).

A comparison with emission measurements was impossible within the research budget and time scale. Fuel consumption records are maintained by ship operators but are not publicly available. Ship operators do not perform measurements of CO_2, SOx and NOx emissions on board as it is not a policy or standard procedure to measure emissions on board ships in operation.

Atmospheric measurements in ports and in the vicinity of ports that identify pollutants from ships can be used as information about local ship emission levels compared to air emission regulations. Methodology exists to distinguish marine diesel emissions from other industrial sources; however, uncertainty is in the ability to quantify emissions, as atmospheric measurements cannot be accurately related to emissions of particular ships in port, as emissions from ships can travel through the atmosphere for hundreds of miles. Therefore, the origin of atmospheric emissions measurements is difficult to trace back to a distinct group of ships or track the location where those emissions were generated.

Considering all possible options, the only adequate verification methodology that enables vessel-based results comparison is a comparison of methodologies. Therefore, the Bottom-up model was developed as an implementation of IMO (2014), as presented in Chapter 3. The

Bottom-up model enabled emissions estimates based on actual ship speed over ground, GPS position and course obtained from AIS historical data.

The SEA method aims to provide a practical tool for, less data and time consuming, yet accurate assessment of emissions from ships in regional seas, ports and coastal waters. The SEA method needs to process the estimation of emissions for numerous ships, so it uses aggregated datasets and averages of ship voyage information to reduce the processing time and data needed for ship emission assessment.

Verifying the SEA method results needed an accurate comparison methodology, which would process the case study AIS datasets of ship activity data and provide a reference of emission estimates per pollutant. The accuracy of the reference is expressed as the percentage error, where the error is calculated as the difference between the SEA method and the reference method results, as presented in section 5.4.

A comparison of the methodologies was conducted, and results of emissions per pollutant were compared for two sets of containership fleets in the following way:

1) For each containership individually
2) Total emissions

The strengths and limitations of the SEA methodology were identified and explained further in this chapter.

5.3 Method Comparison

A ship activity data is needed to estimate energy demand and, consequently, fuel consumption directly linked to emissions.

The SEA method applies novel concepts to estimate ship activity data (ship speed, activity time and distance) using the average voyage parameters.

Ship voyage parameters are:

1. Average voyage speed
2. Voyage distance
3. The time that a ship spends in each activity phase (cruising, manoeuvring, anchoring, berthing)

Voyage parameters determine the Main engine load factor (LF), as explained in Chapter 4, Equation 4.8. The estimated parameters listed above are used to establish ship total energy demand, which is multiplied by energy-based emission factors and used to estimate emissions for different pollutants, CO_2, SO_X and NO_X, as presented in Chapter 4.

Both of the compared methodologies use the bottom-up principle to estimate emissions for each vessel and then calculate total emissions as the addition of emissions generated by individual vessels.

The main difference between the methodologies is that the SEA method uses a voyage-based approach to acquire input data, from average voyage ship speed and averages for ship activity from the entry to the exit of the defined boundary. The Bottom-up model uses AIS data to define vessel position, course and speed over ground, which is a more precise and detailed approach. However, the SEA method takes one-tenth of the time for the same number of ships compared to the Bottom-up model. The unit to compare time processing needed is the time needed to process one data record and the interlinked input, as explained in Chapter 3, Section 3.4.4

The differences and similarities between the two methods are analysed and presented in Table 5.1.

	LF MAIN ENGINE	*TIME AT BERTH* *[h]*	*TIME SPENT IN THE ACTIVITY PHASE* *[h]*	*AVERAGE DISTANCE CRUISE* *[nm]*	*CRUISE SPEED* *[kn]*	*MANOEUVRING SPEED* *[kn]*
SEA method	$\mathrm{LF_{cruise}} = \left(\frac{\mathrm{V_{Sea\ Speed\ Average}}}{\mathrm{V_{MCR}}}\right)^{n}$	Time at berth obtained from Port calls data	$\mathrm{T_{cruise}} = \frac{\text{Average Distance}_{\text{cruise}}}{\mathrm{V_{voyage-average}}}$ $\mathrm{T_{man}} = \frac{\text{Average Distance}_{\text{man}}}{\mathrm{V_{Sea\ Speed\ Average}}\ \mathrm{x}\ 0.3}$	Average Cruise distance obtained from Ship Tracks Map	Average Voyage Speed – average speed for last ship log, obtained as Voyage data package	$\mathrm{V_{man-average}}$, average manoeuvring speed
Vessel-based method	$\mathrm{LF_{cruise}} = (V_{SOG}/V_{MCR})^{3.5}$	Time lapsed btw. first and last AIS signal, for V_{SOG} <1.5kn	$\mathrm{T_{cruise}}_{\ i}, \mathrm{T_{man\ i}} = \sum\left(\frac{d_i}{V_{SOGi}}\right)$	d - distance between the two nearest AIS points of call	V_{SOG} – speed over ground (AIS)	V_{SOG} – speed over ground (AIS)

Legend: d - the distance between the two nearest AIS points of call
V_{SOG} – speed over ground at the AIS point of call
$V_{man-average}$ - average manoeuvring speed , $\mathrm{V_{voyage-average}}$- Average Voyage Speed

Table 5. 1: Differences and similarities between the two methods table

Both the SEA method and the Bottom-up model used EFs from the Fourth IMO GHG Study (2020). to quantify emissions of CO_2 and SO_X, while IMO NO_X regulatory emission levels were used to determine NO_X.

Auxiliary boiler power usage and emissions were not considered when comparing results, as that part of the estimate adds equal assumed values to both methods and therefore does not impact the methods' results.

5.4 First sample: 20 container ship voyages 15nm port boundary

To validate the SEA methodology, different containership sample sizes were explored, and two different port boundary distances were tested. The first research sample analysed a total of 20 voyages from two different vessels to the same port, with the port boundary distance set to 15nm. CO_2 emission estimates were obtained for the 20-ship dataset using the SEA method and Bottom-up model. The CO_2 emission quantities obtained by the two methodologies were compared for each individual ship voyage and total emissions for all voyages.

In this series of tests, identical EFs were used for both methods; however, there are differences in the results due to voyage parameters: cruising and manoeuvring distance, time spent in each ship activity (cruise, manoeuvre, anchor/berth), and speed. The results of the total emissions are compared in Figure 5.1.

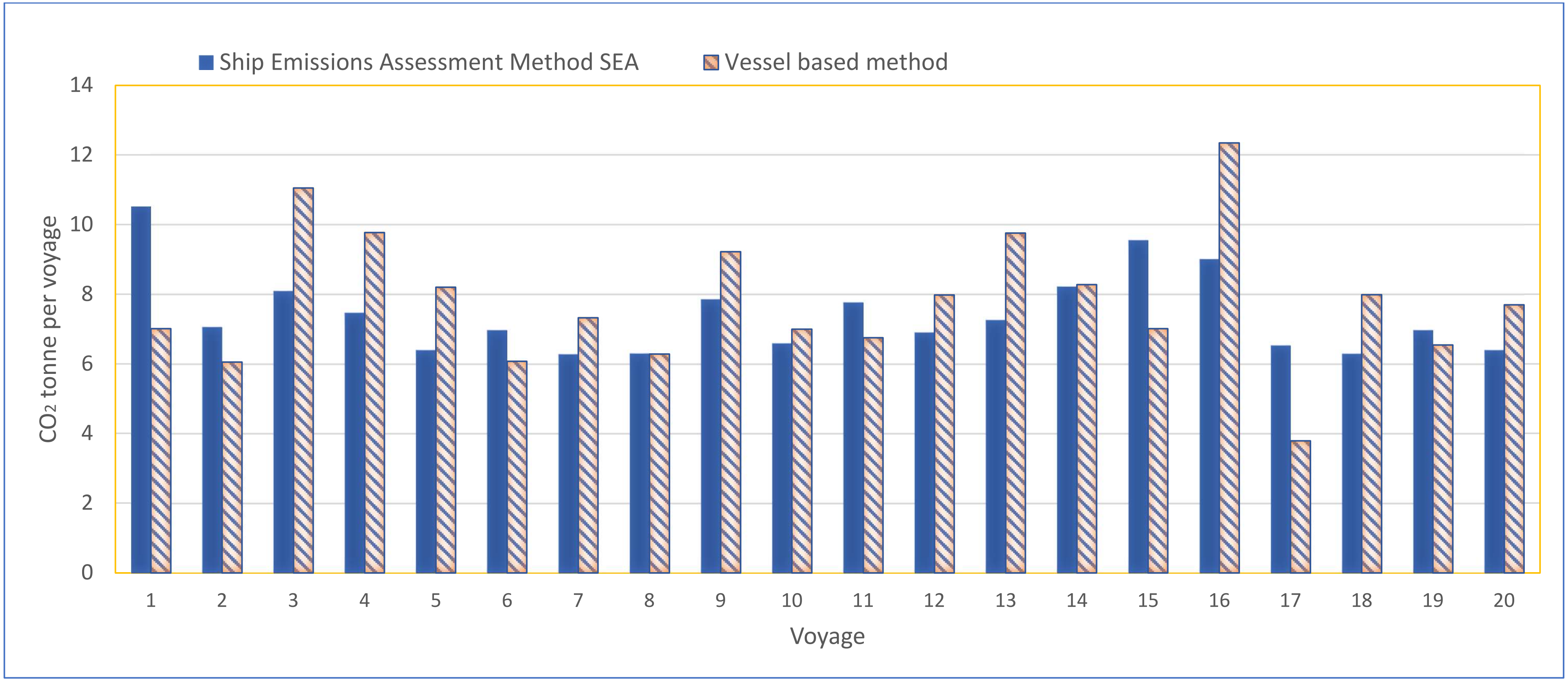

Figure 5. 1: Results compared between the Ship Emissions Assessment Method SEA and the Bottom-up model

It can be observed that for a single ship voyage, CO_2 emission estimates using the SEA methodology could differ from the Bottom-up model for a single case voyage on average by up to 40%, which depends on how much a specific ship diverts from the route of highest ship track density used as the reference route by the SEA method. The route of the highest ship track density is the route of the highest probability obtained as a yearly average. Therefore, although one ship might divert from the average route due to different circumstances, the closer the number of ships in the sample is to the total number in the one-year average, the closer will be the match in the results.

For the one year of ships in the sample, the average of the cruising route distance would be the same, whether it is estimated on a ship-by-ship basis and then aggregated, or it is taken top-down and measured from the spatial aggregated ship track density.

Most vessels would follow the route of the highest probability, and although some anomalies can be expected, all of the ship tracks, including the anomalies, are included in the aggregated ship track average. The SEA method assumes cruising distance as the highest probability route, measured against the one-year route of highest ship trajectory density. Consequently, the difference between the average route distance obtained by the SEA method for the selection of ships and the average distance obtained using the Bottom-up model will reduce with the increase in the number of voyages in the sample.

The comparison of individual vessel emissions obtained by both methods is presented in Figure 5.2. The difference in aggregated results of quantified emissions for CO_2, obtained by both methodologies, is then presented in Table 5.2.

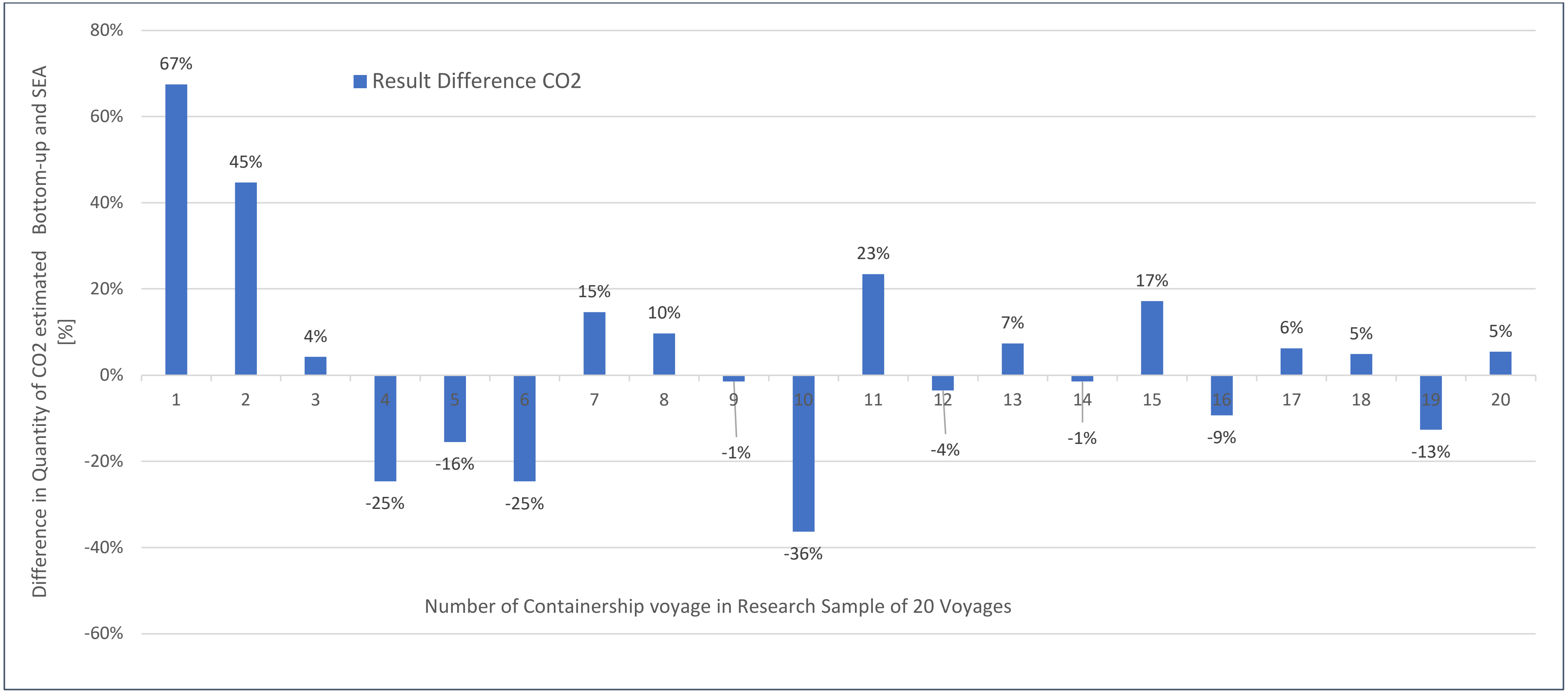

Figure 5. 2: Difference in results of CO_2 emissions, SEA Method compared to the Bottom-up model

When the novel SEA method's outcomes (total emissions for all voyages considered) are summed up and the results that cancel each other out accounted for, there is less than a five per cent difference between the Bottom-up model and the SEA method, as presented in Table 5.2.

	SEA Method	**Bottom-up model**	**Result Difference (tonnes CO_2)**	**Result difference %**
Total Emissions of all voyages [tonnes of CO_2]	148.31	156.07	7.75	4.97%

Table 5. 2: The Ship Emissions Assessment SEA Method results compared to the Bottom-up model results

5.5 Second sample of container ship voyages, 20nm port boundary

A second sample of 100 containership voyages was obtained for the Port of Rijeka regional area. AIS data was obtained for the Voyage-based methodology, and voyage-based data combined with ship density map information was obtained for input to the SEA method.

Ship technical information acquired from Clarkson's Research portal was used for both methods.

The research was conducted to test how the SEA method emission estimates would compare to the Bottom-up model for a five times larger sample than in the first case. The second sample of containerships contained a selection of containerships of the range of sizes and engine powers, from 500 to 15500 TEU and from 2000 to 15500 kW. Several ships in each size range were selected, and additionally, a representative sample of ships with the highest number of voyages to the port in one year was selected from each ship size bin.

Emission factors for each ship were obtained using the same rules as explained previously in Chapters 3 and 4 for both methods. Most ships used conventional diesel engines, while less than

10% had diesel-electric engines. The difference in emission factors due to the different years of build of the engines was obtained using the same input algorithm for both methods.

However, the Bottom-up model obtained main engine load factors using the actual speed ratio divided by the maximum engine speed, while the SEA method obtained the load factors using the innovative approach explained in Equation 4.9, Chapter 4.

From the selected 100 voyages, 95 had sufficient data to complete the SEA method estimate. However, a more detailed Voyage-based method could not be performed for some ships, as data was missing or contained record errors. After cleaning the data, 75 containerships had sufficient data to be applied in the Bottom-up model. Four other voyages were eliminated from the research sample because the dates of arrival and departure of the ships at the port, which were obtained through historical AIS data, did not match the dates of ship arrivals and departures obtained through port report data used for the SEA method. The reason for this might be that the ships were anchoring within the port boundary, but only the berth time was recorded.

Erroneous data records (29) were eliminated from the sample, and the methods were then compared for 71 voyages.

A comparison of the CO_2 emissions from the SEA method and the Bottom-up model is presented in Figure 5.3. The comparison of NOx between the SEA method and the Bottom-up model is presented in Figure 5.4.

The distribution of the results from the two methods is expressed as a percentage, and the difference in quantified results is presented for CO_2 in Figure 5.5 and NOx in Figure 5.6.

Aggregated result differences fall in positive and negative directions from the mean value, as shown in Figures 5.5 and 5.6. The aggregated results for each pollutant are compared in Table 5.3.

It can be seen from Figures 5.5 and 5.6 that the aggregated errors for the emissions would approximate zero, given the fairly even distribution of positive and negative values.

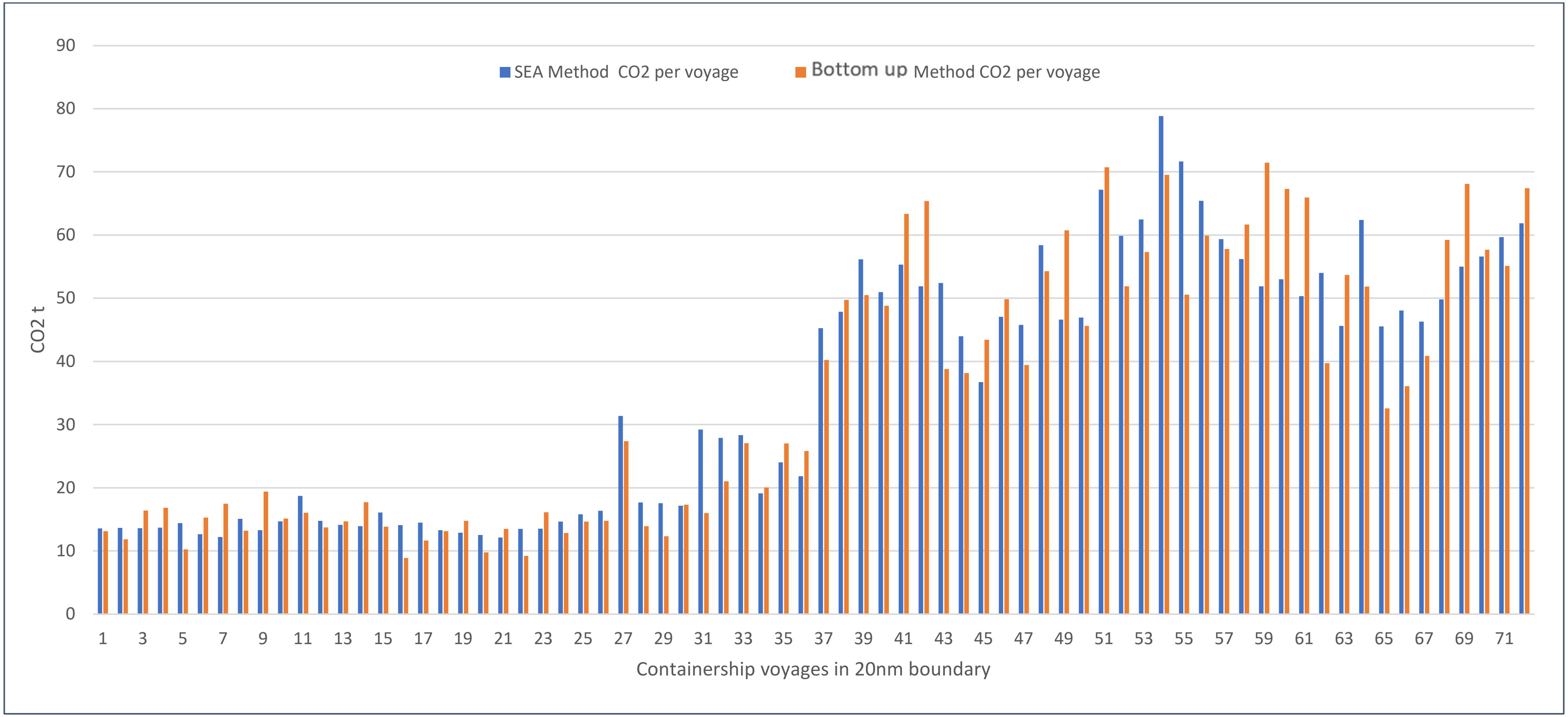

Figure 5. 3: Comparison of the emissions of CO_2 between the SEA method and Bottom-up model for 71 containerships

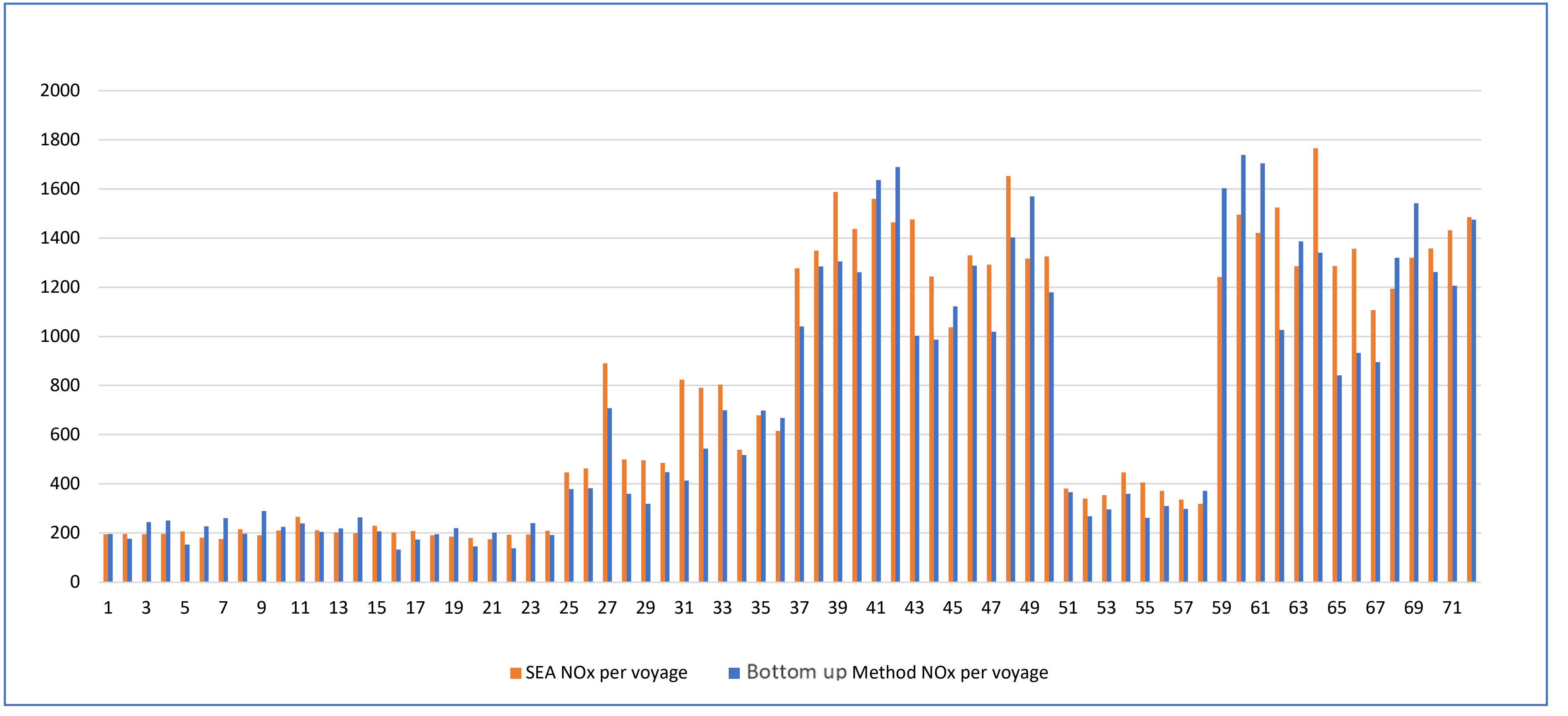

Figure 5. 4: Comparison of the emissions of NOx between the SEA method and Bottom-up model for 71 containerships

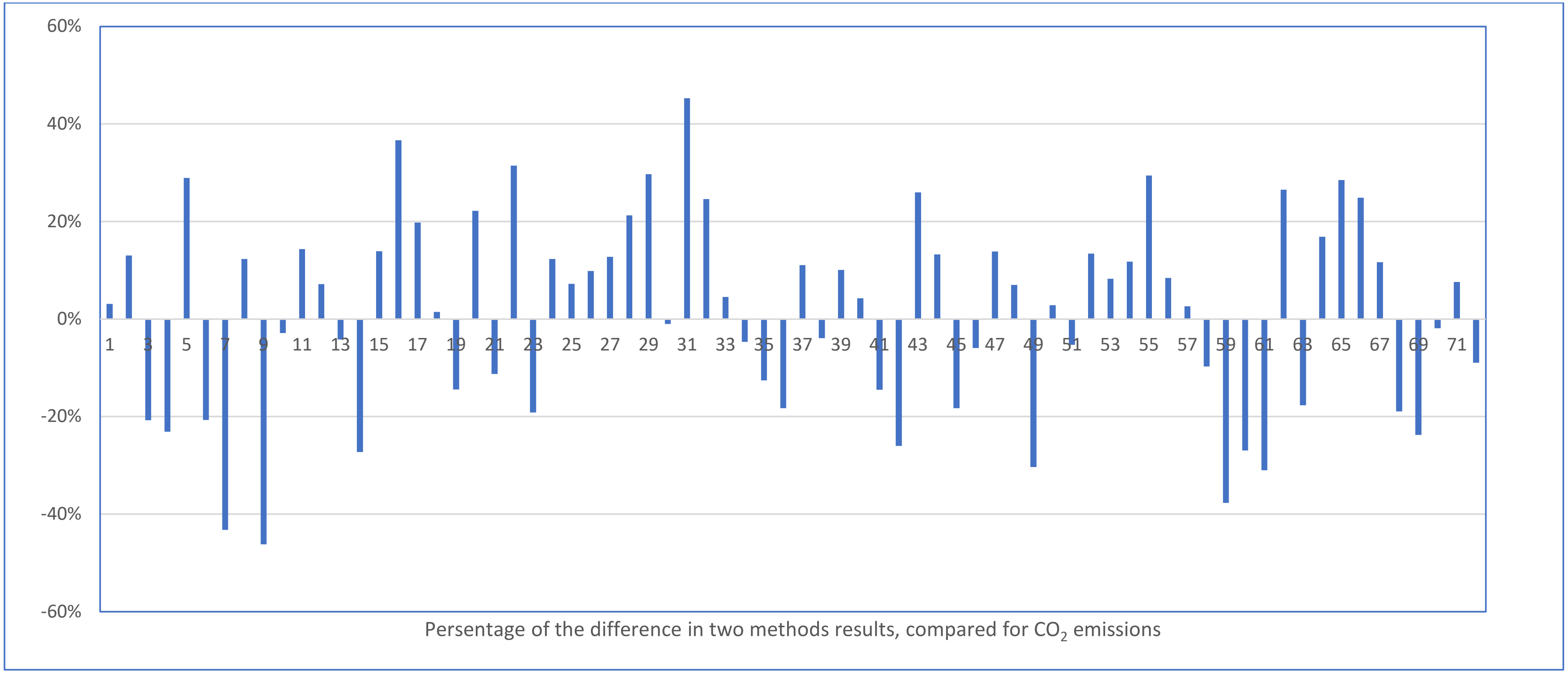

Figure 5. 5: Distribution of the results from the two methods, the difference in percentage for CO_2

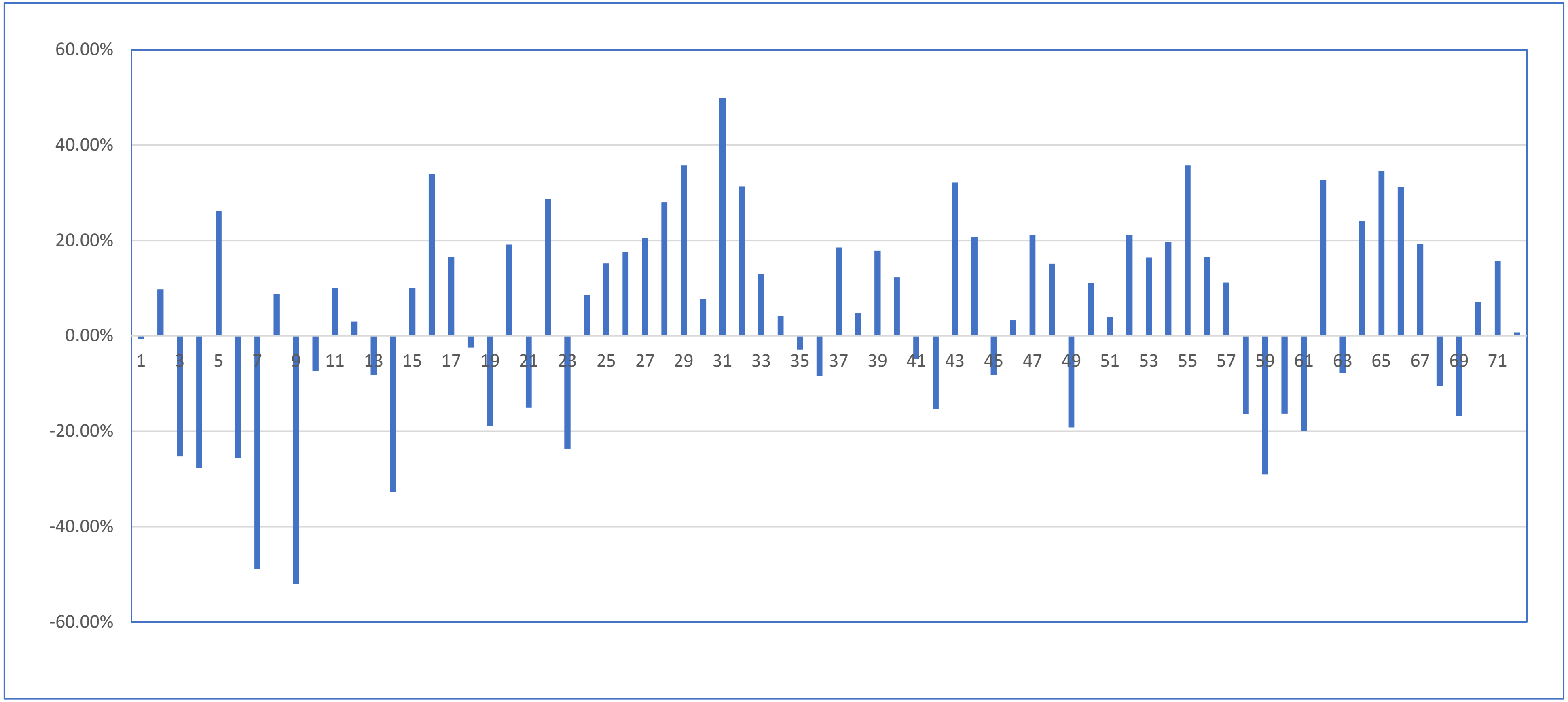

Figure 5. 6: Distribution of the results from the two methods, the difference in percentage for NOx

Bottom-up Method	**SEA**	**Bottom-up Method**	**SEA**	**Difference CO_2**	**Difference NO_x**
CO_2	CO_2	NO_x	NO_x	%	%
2,172 t	2,213 t	44,7 t	49,1 t	1.87%	8.94%

Table 5. 3: Ship Emissions for 71 voyages of containerships in the 20nm port boundary, the SEA method compared to the Bottom-up model

The results show that differences between the two methods in individual ship voyage results scatter approximately equally in the positive and negative directions. Consequently, aggregated emission results compare well, with a less than two per cent difference for CO_2 and under nine per cent difference for NO_x. It can be concluded that for the second sample, which is nearly four times larger than the first sample, results for CO_2 emissions compared better than in the first sample.

To conclude, results for the SEA method compare well to the Bottom-up model once the results from both methods are aggregated for all voyages. It is reasonable to expect the reliability of the results from the SEA method to further increase with the sample size as the aggregated results average is getting closer to the one-year average.

5.6 SEA method NOx emission estimates compared to the *bottom-up* method using average installed power and emission factors

The bottom-up methodology, which uses constant emission factors (Peng et al., 2020), was implemented to compare the results with the SEA method, which considers ship YOB and technical measures to identify emission factors for the individual vessel. The bottom-up methodology applied assumptions from (Peng et al., 2020), which assumes that most ships use MSD engines and fuel with 0.2% sulphur content as a mean value. Both models, the implementation of (Peng et al., 2020) and the SEA methodology, were applied using the same data record of 500 containership voyages to the port of London.

The estimated emissions for NOx from both methods were compared to understand the difference in emission estimates based on average EF factors and estimates considering vessel NO_X standard compliance.

The 500 containership voyage emissions were estimated using the one-year historical data. Results for the quantification of NOx obtained by the Peng (2020) bottom-up and SEA methods are presented in Figure 5.7.

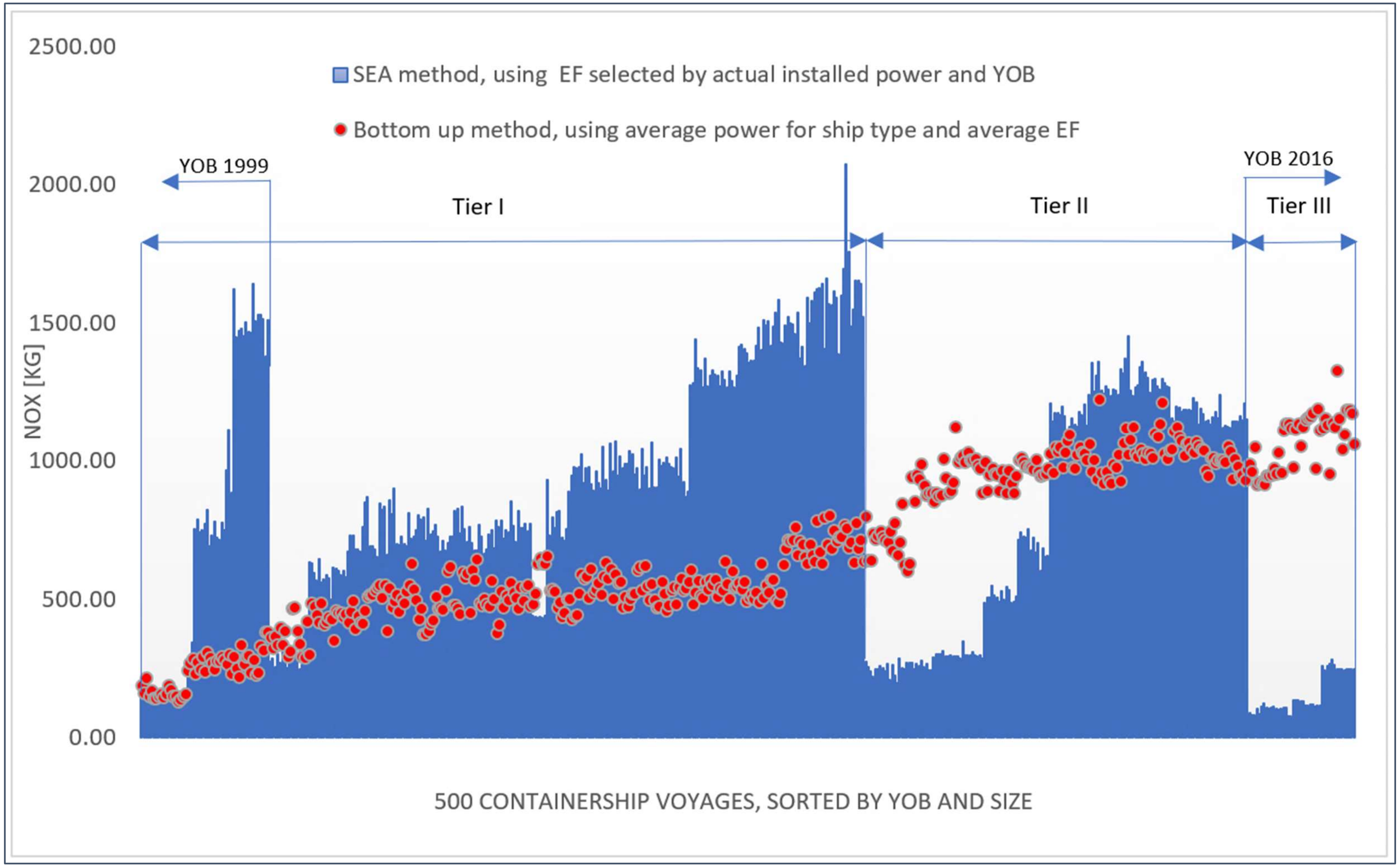

Figure 5. 7: Comparison of estimated yearly NOx emissions generated by containerships, demonstrates higher reliability of the SEA method compared to Bottom-up method

The graph in Figure 5.7 shows that the SEA method reflects the distribution of NOx emission by engine type and according to the current IMO Tier III emissions limits.

However, the bottom-up method emission results do not consider fluctuations in emissions due to the engine type and compliance with engine emission standards. Thus, although more detailed, the bottom-up method using average values for emission factors cannot accurately reflect compliance with the emission reduction regulatory measures.

The SEA method delivers quantification of the emissions from the ship exhaust, which is sufficiently accurate to understand the impact of regulatory measures on ship emission performance.

The uncertainty remains as to the extent to which ships in operating conditions comply with the standards due to seagoing conditions, human factors, and other unpredictable causes. This uncertainty can only be thoroughly resolved using onboard measurements of the ship exhaust and fuel consumption records. Since those records are difficult to obtain, the SEA method provides a practical and accurate solution for assessing emissions from ships in designated areas.

5.7 Comparison of the SEA method and the Bottom-up model, operating times and quantity of data

This section compares the SEA method to the Bottom-up model in terms of data acquisition time and quantity, data costs and overall time to perform both methods in the same conditions. Conditions were the one-time download of historical data, usage of the internet only during the data download and processing on a standard personal laptop with an i5 processor, which is the standard accessible to most shipping stakeholders globally. The SEA methodology reduces the time of data acquisition and quantity of ship activity data compared to the Bottom-up model. A schematic example of the minimal quantity of data needed for the Bottom-up model vs the SEA method is presented in Figure 5.8. A different way of data acquisition is explained, for the example of a single ship, ½ voyage to the port. The green colour represents cruising speed, while orange and yellow shades in the ship track represent manoeuvring activity, in this case, deceleration distance. The red shades represent slow speed under three nautical knots.

Figure 5. 8: Schematic presentation of voyage data acquisition using the Bottom-up model vs SEA method (Marine Traffic, 2020)

Figure 5.8 presents a schematic visualisation of cruising and manoeuvring distance, obtained by calculating distances between AIS points of call. In Figure 5.8, AIS signals are represented by location signs and a white square. In contrast, the SEA methodology measures the distance along the existing ship track, readily available in commercial portals (Marine Traffic, 2019; Clarkson's Research, 2019). The SEA uses average values for cruising and manoeuvring speed, as explained in Chapter 4, Table 4.4. The application of the SEA methodology, as presented in Figure 5.8, works best for emissions estimates of individual vessels or samples less than 20 ships because it resembles the Bottom-up approach in accuracy. This approach requires measurements of the past track of each individual ship, and it is used to calibrate the SEA methodology for each new geographical area and establish average cruising and manoeuvring distances in port.

For assessment of emissions of a significant number of ships (more than 20, as explained in Chapter 5), the SEA method determines the cruising distance using the historical ship track, whose distance is measured along the historic ship lines or the highest density route. The SEA method bridges this by using the average route and voyage average speed, first allocated from the spatial map of historical ship tracks, which are plotted on the same map for the one year of shipping traffic on any location globally.

These signals contain data records, which were explained in Chapter 4. To estimate emissions for one ship voyage to and from the port within the port boundary measured radially from the port, the Bottom-up model requires a minimum of 50 AIS data records (20nm boundary). Those 50 records would consist of 2x17 records for entry and exit to the port and more than 16 records for the time in the port if a ship is detained by port operation and anchorage for 4 hours and signals are received every 15 minutes. The average value of 50 data records was used to estimate the time needed to use the Bottom-up model under the same conditions as the SEA methodology and one historical data download.

Tables 5.4 and 5.5 compare data quantity, price of data and time needed to estimate emissions for 1200 containerships using the SEA vs Bottom-up methodology.

<u>SEA Methodology</u>
Task: Assessment of one-year containership traffic within the 20nm port boundary
Number of containership voyages: 1200

Data Acquisition	Data Quantity	Cost of Data	Time for Input and Clearing of Erroneous Data
Technical Data Ships	The input of 1200 technical ship data, MCR, RPN	1-month subscription: £90	0.5 min/data record Total: 10h
Voyage Data, Average voyage speed	1200 data records	£45 for purchase of average voyage data	40 min
Ship phase allocation, Distance travelled within the boundary	Ship Density Map	£7 one-month subscription	60 min
TOTAL	2400 data records	**£142**	**11.67 h**

Table 5. 4: Data, Cost and Time to process SEA methodology for 1200 containerships

<u>Bottom-up Model</u>
Task: Assessment of 1200 containership traffic within the 20nm port boundary

Data Acquisition	Data Quantity	Cost of Data	Time for Input and Clearing of Erroneous Data
Technical Data Ships	The input of 1200 technical ship data, MCR, RPN	Clarkson's Research (aprox.£5000/year) Or One-off data purchase download approx. £2500	0.5 min/data record 10h
Voyage data acquisition, input, boundary conditions, processing and erroneous and gap data processing	60000 AIS data records		Average of 5.5 min / ship voyage 6600 min = 110 h = 4.6 days
TOTAL	61200 data records	**£2500 - £5000**	**110 h**

Table 5. 5: Data, Cost and Time to process Bottom-up methodology for 1200 containerships

The SEA methodology can be applied 9.4 times faster than the Bottom-up method, using conventional laptop and office for windows 10. The bottom-up methodology was performed using a subscription to Clarkson's Research as the best option available; however, if the lower-cost data was used, the Bottom-up methodology would take longer to perform due to 10% more erroneous and gap data in the Marine Traffic portal compared to Clarkson's Research portal.

Both resources are publically available at cost; however, the SEA methodologies reduce 35 times the cost of data and 50 times the size of the dataset.

The SEA methodology requires several hours of internet connection for a one-off download of data, after which it can be run independently of the internet. It can therefore be used in ports and places with weak internet connections, like on board ships. It is cost-efficient and therefore applicable to stakeholders with limited budgets; it does not require high-level programming skills, which makes it more affordable and applicable to small to medium size shipping businesses, and port and regional authorities globally.

The SEA method uses ship voyage route length data from historical ship tracks and therefore does not require AIS data to recreate historic ship activity. The average voyage speed is used as a proxy for actual ship speed. The methods will have comparable results to the Bottom-up model if the same ship technical details are used in both methodologies and the same emission factors. However, the SEA method will require one input for ship cruising length and speed, compared to a minimum of 50 data records required by the Bottom-up model. This means that the SEA method requires 1/50th of the data used by the Bottom-up model for the same ship making the same voyage to the port.

The SEA method provides bottom-up estimates of ship exhaust emissions, which are accurate for geographic area emission assessment purposes. Additionally, the SEA method can be applied for forecasting the levels of emissions from ships in the event of changes in regulatory measures. The SEA method allows input and change of emission factors which enables estimation of emissions in case of the potential changes in regulations or changes in current shipping fleet technical measures. The SEA method will use 1/10th or less time to perform, from data acquisition to results, than the Bottom-up model applied in equal conditions,

5.8 Summary of Chapter 5

The SEA method required validation which was achieved by comparing results against the more detailed Bottom-up model. The validation method was applied as explained in Chapter 3, Section 3.3. Two samples of different sizes for one year of containership voyages were compared for emission estimate results. The first sample had 20 containership voyages of one vessel arriving at the same port for one year. Here it was demonstrated that the SEA method is applicable, and aggregated results are comparable for one year of a single vessel travelling to the same port.

The second sample compared a sample of 71 containerships, with one year of traffic, for both methods. This comparison shows that the SEA method uses a tenth of the time to calculate large datasets, as it requires between 50- and 500-times fewer data records for processing and 1/10th to 1/100th of time compared to the Bottom-up model, as presented in Section 5.7.

Time can be expressed in terms of The SEA method using an inexpensive and widely accessible dataset, previously not used, to supplement historic one-year AIS data acquisition. Finally, Section 5.5 compares the SEA method and the bottom-up methodology that uses a constant emission factor as a proxy. This comparison shows how the SEA method calculates changes in ship emissions due to technical abatement measures on ships, which could not be detected by methods that rely on constant emission factors.

The SEA method comprises elements of top-down methodologies to optimise data requirements of bottom-up methodologies; however, the SEA method results are comparable to Bottom-up model aggregated emission estimates. To conclude, the SEA method is a practicable tool to estimate emissions of ships in designated areas to understand regulations' effectiveness and provide emission quantification evidence.

Chapter 6. Comparison of Ports for Ship Emissions and Reduction Measures Efficiency

6.1 Introduction to Chapter 6

The SEA methodology was applied to compare emissions generated by containerships per unit of transported volume of cargo (TEU) for three containership ports, Rijeka, Trieste and Venice, situated in the North-West Adriatic Sea basin. The reason for the choice of the location is that there are no publicly available ship emission inventories for the ports of the North Adriatic Sea. The Adriatic Sea is not classed as a NOx Emission Control Area (NECA), and outside the ports, it is not classed as SECA, although its coasts are either densely populated or natural protection reserves, and the enclosed nature of the sea makes it sensitive to eutrophication caused by NOx and SOx. This means that the National regulations of countries sharing the Adriatic Sea coastline do not require the strictest Tier III NOx standard, and consequentially the NOx emission levels from ships remain unregulated and their quantities unknown. The emissions of SOx are regulated in European Ports to restricted levels of 0.1% of sulphur content in fuel; however, outside the ports, 0.5% limits apply, and it is not assessed whether this measure can effectively mitigate the increase in emissions driven by the rapid growth in shipping intensity (Chapter 1).

Therefore, this Thesis objective was to apply the SEA method to quantify containership exhaust emissions for the three significant containership ports in the North of the Adriatic Sea. The SEA method results were presented as quantified CO_2, SO_X and NO_X emissions for the selected areas, further divided by the throughput of containership, to obtain comparable emissions in grams of pollutant per transport of a container (TEU).

6.2 Case study areas characteristics

Ports of Rijeka, Venice and Trieste share the same feature of being the last port-stop for ships arriving in the Adriatic Sea. Therefore, all traffic calls to the designated ports within the boundary, and as a consequence, emissions generated by containerships in the boundary could be assigned to ships calling to the port. This is significant as historic ship tracks used for this Thesis research were further explored for quantified emission spatial presentation. Quantified emissions were distributed along the historic ship tracks to the present, where emissions are generated (Chapter 4).

The basin of the Adriatic Sea provides the shortest and, therefore, the cheapest shipping traffic routes between central and Northern European countries and the Suez Canal and the Middle East and Asia trade zones. This has resulted in an increase in containership throughput and traffic intensity through the Adriatic Sea by 57.8% between 2009 and 2019 (Beškovnik et al., 2019). The three significant containership ports, Rijeka, Trieste and Venice, have increased their capacity by 20% during the same period. Containership traffic density for ports is presented on the spatial ship historical track density map in Figure 6.1.

The North Adriatic area is densely populated, and the economy relies heavily on tourism based on natural reserves and historical heritage. This situation requires regular assessment of emissions to the air generated by ships to provide decision making bodies with the evidence needed to impose effective reduction measures. Containerships are the highest polluting ship type globally (IMO,2020), and their activity needs regular and transparent emissions inventories for NO_X, SO_X and CO_2.

The application of the SEA method and its results are presented further in this chapter.

Figure 6. 1: Ports Venice, Trieste and Rijeka presented on the containership density map (Marine Traffic, 2019)

6.3 Implementation of the SEA methodology explained in the case study of the Port of Trieste

The SEA methodology estimates CO_2, SO_X and NO_X emissions as explained in Chapter 4. This section explains the implementation of the SEA method to estimate emissions in the case study ports.

Port traffic organisation data were acquired for each port and entered into the SEA method. The SEA method has two types of input data: bottom-up ship technical data and top-down voyage-based data. Emission factors selected were regulatory levels used in all ports for comparability of results and understanding regulation effectiveness.

Top-down voyage data is acquired for ship voyages in the required time and port. This includes technical data related to ships and the voyage parameters:

1) Voyage speed average ($V_{voyage-average}$), obtained from the Marine Traffic System
2) Averaged sea speed for containership capacity size bins ($V_{Sea\ Speed\ Average}$)
3) Maximum rated speed (V_{MCR})

Voyage speed average ($V_{voyage-aver}$), is the average speed between the port of destination and port of departure, which includes speeds of the ship within the research boundary and speeds along the route to the last visited port.

Average speed presents an average of ship speed over ground values, and the speed over ground is subject to the impact of the external weather and sea factors. The SEA method estimated the main engine energy demand for one hundred containership voyages throughout all seasons in one year, which was compared to the AIS-based Bottom-up method results, as previously explained in Chapter 5. The two methods were compared with less than a 2% difference, subsequently showing that the weather and other external factors did not impact the accuracy of the rapid SEA method estimates in the research area of the North Adriatic. However, the limitation of the SEA method is that each new port and research area needs to be initially evaluated for ship patterns and weather and sea conditions before the SEA method can be applied. Although identifying the exact weather influence is not crucial to providing rapid ship emissions evidence for improving policies and regulations, different locations globally could have severe weather or sea conditions that need to be considered. In that case, better accuracy of the SEA method could be achieved by using a season-dependent average of ship manoeuvring and cruising speed instead of one year average.

Acquisition of top-down data from ship density maps and allocation of ship activity phases was set according to the traffic organisation of each port and speed-dependent average cruising distance, measured across the historic ship tracks (Chapter 4). Each case study port area required input of distances that ships, on average, cross at cruising speed. This part of the process responsible for ship track analysis is highlighted in the SEA method diagram in Figure 6.2.

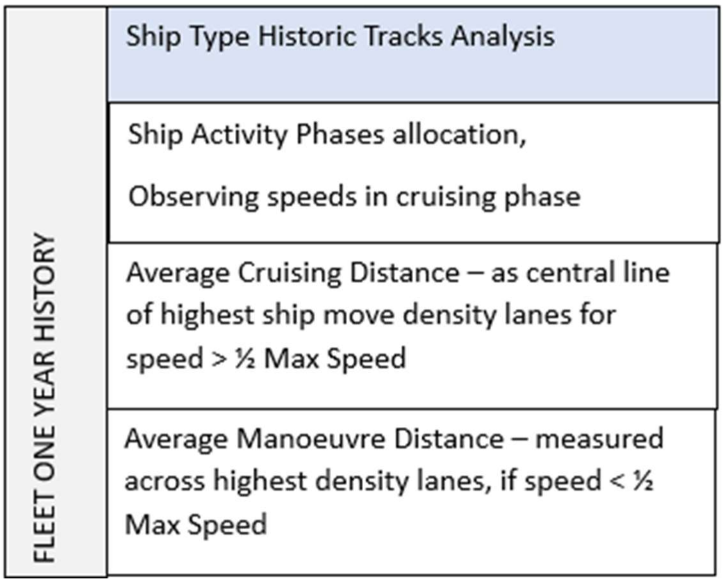

Figure 6.2: The part of the SEA method process in charge of cruising and manoeuvrings distance determination

Average manoeuvring and cruising distances need to be identified to apply the SEA method to the new location. Regional seas with a high density of shipping traffic have organised nautical lanes for ships, and the route of the highest density of ship trajectories can be selected from ship density maps. This was explained in Chapter 4, using the case study for the Port of Trieste and the SEA application for that port. The application of the SEA method to estimate emissions of CO_2, SO_X and NO_X from containerships for the other two ports, Rijeka and Venice, uses the same process.

On the northwest side of the Istrian peninsula, the Port of Trieste has a completely open entry to the port and no artificial or natural barriers. To identify the cruising and manoeuvring stage along the ship tracks, it is necessary to observe a sample of ships and obtain ship speed patterns along the entry and exit routes, i.e. when ships lower speed to half of cruising speed on entry to the port and when they increase speed to cruising speed at the port exit (presented in Chapter 4). This ship speed sampling needs to be done once for each port. The route pattern and the choice of the entry and exit routes are presented in Table 6.1 and the process that selects the route of highest density was presented previously in Chapter 4, Figures 4.4 and 4.5.

Figure 6.3: Speed and manoeuvring distance analyses (Chapter 4, figures 4.4 and 4.5.) on the example of one containership trajectory. The smaller image presents the same track position on the ship density map.

	Average distance in cruising phase [nm]	***Average manoeuvring distance [nm]*** *IF T_{port}>24,* ***(Assumed anchorage distance included)***	***Average manoeuvring distance [nm]*** *IF T_{port}<24* ***(No anchorage)***
Port entry	17.9	4.7	1
Port exit	17.2	0.5	0.5
TOTAL	15.8	5.2	1.5

Table 6. 1: Port of Trieste - ship cruising and manoeuvring data specific to port and location

Data in Table 6.1 presents an input for the SEA method. Containership average route to enter the port and reach the berth location is measured in nautical miles, along the central line of the densest part of the historical ship tracks (referred to in the further text as: the route of the highest density) and assumed to be the average distance ships would travel.

This data is specific for each port, and it can be reused to assess ship emissions in a selected port for the selected year if there are no significant changes in regulation, port traffic management systems or infrastructure developments which might impact the shipping traffic lanes. Once the average voyage values are set, they are used as an input to the bottom-up part of the SEA method as a proxy of voyage parameters for individual vessels within the boundary. As explained in Chapters 4 and 5, the limitation of usage of average data is that individual ship emission estimates can differ up to 65% from Bottom-up model estimates; however, for 20 or more ships, aggregated emissions will compare well to Bottom-up model estimates, because differences tend to cancel each other out, as the number of voyages closes to the number of ship tracks in the yearly average.

Therefore, in the case of a smaller sample of fewer than 20 ships, the SEA methodology can be applied differently. Instead of average values based on the one-year ship past track map, individual ship past track can be used for individual vessels, as demonstrated in Figures 5.8

and 6.3. The SEA can operate as a bottom-up methodology for individual vessels; however, the SEA methodology’s primary aim is to be applied for the significant number of ships in designated geographical areas, in which case the SEA methodology is best used with average top-down voyage data which enables the practicality of the top-down method.

6.4. The SEA method applied to the Port of Rijeka

The seaport of the Rijeka case study area is a natural 11nm long and 10nm wide bay, allowing unrestricted ship movement. Ships calling to the port of Rijeka have unlimited anchorage space, and the flow of traffic at the port entrance has no physical barrier to direct it. However, it is still possible to identify shipping routes of entry and exit from the berth and locations where ships start decelerating from cruising speed to manoeuvring speed.

Most ships start reducing speed before or during the natural channel between the island of Cres and the Istrian peninsula, closely after the port's designated 15nm research distance. The unmistakable landmark is the lanterns (lighthouses), signifying the channel's narrowest part, as presented on the ship density map in Figure 6.4. The analysed ships show a pattern of manoeuvring phase location, as presented in Figure 6.5.

The sample of ship tracks presented on a geographical map and compared against the AIS system provides a reasonably fast and accurate estimate for ship routes and speed patterns within the port boundary. This process needs to be put in place the first time the AIS methodology is applied to a port and if there are any changes in port traffic managerial or regulatory measures.

External conditions, like wind, tides and waves, impact ship speed and routing. Average ship route based on the one-year ship tracks history includes the impact of weather throughout the year to ship directions of navigation and creates the average. The impact of weather to ship speed is included in the average ship speed, which is considering the average speed on the ship voyage between the port of destination and the port of departure.

However, once the pattern of ship manoeuvres and cruising distances within the port is established, it serves as an input to the SEA method, which can be applied to an unlimited number of ships for the selected ship type, calling at the port, to estimate emissions of CO_2, SO_x and NO_x.

The size of the ship sample needed to estimate the average manoeuvring distance with a reoccurring pattern would depend on port managerial measures and geographic circumstances. In three researched ports, the smallest sample (20 ships) was observed for the Port of Venice due to the structural features which physically restrict and define ship movements and speed. The most significant sample was needed in the Port of Rijeka (70 ships) due to the least restrictive anchorage location within the bay.

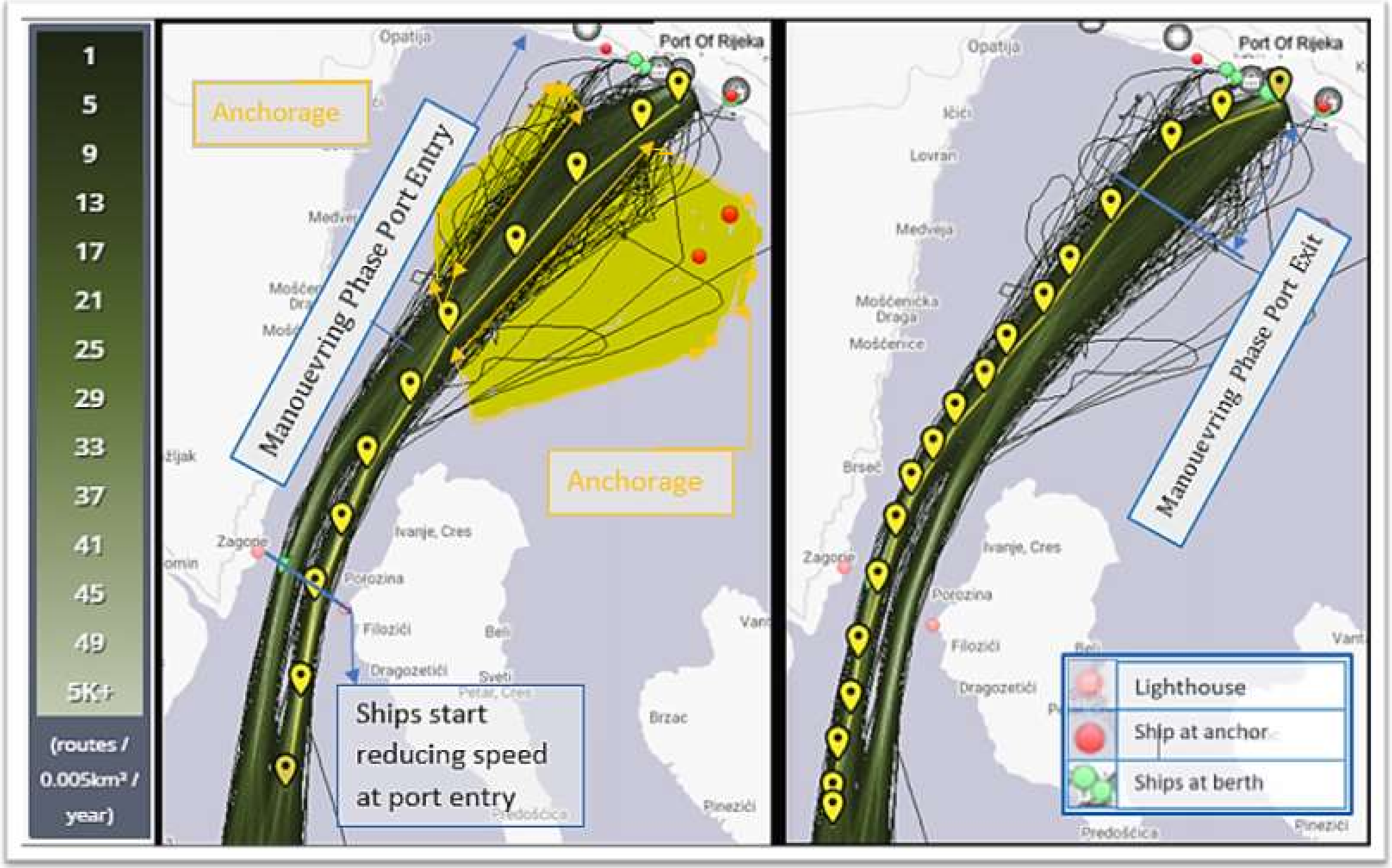

Figure 6.4: Estimating entry and exit containership routes to the Port of Rijeka on ship density maps. The manoeuvring phase at entry and exit from the Port of Rijeka is presented, and two ship anchorage locations are identified.

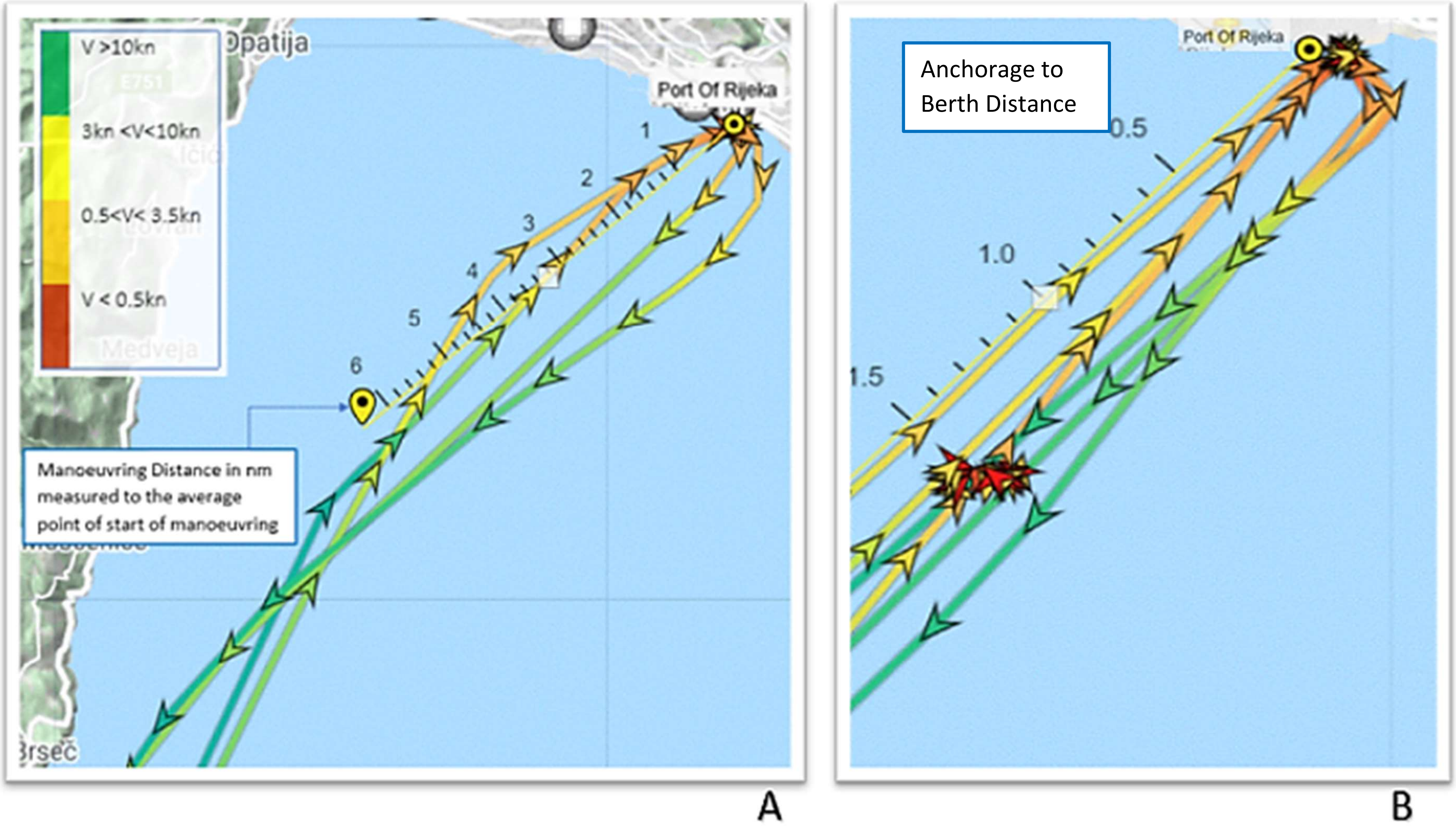

Figure 6.5: Analyses of manoeuvring distance for multiple visits to the port of vessels A and B, A: a case study of a direct port entry and B: a case study of manoeuvring in case of anchorage time

Observed anchorage distances show that ships in the bay of Rijeka anchor very close to the route, which is why no extension was added to the length of manoeuvring due to anchoring. However, emissions generated during the anchoring were estimated using the information about the time ships spent hoteling within the port boundary.

Table 6.2 presents how the ship entry route (Port entry) has a different length and ship phase pattern from the port exit.

	Average distance in cruising phase [nm]	***Average manoeuvring distance [nm]***	***Average manoeuvring speed [kn]***
Port entry	13.3	2.9	3.72
Port exit	13.3	0.5	3.72
TOTAL	26.6	3.4	

Table 6. 2: Port of Rijeka - ship cruising and manoeuvring data specific to port and location

6.5. The SEA application to the Port of Venice

The Port of Venice is an example of a port with limited ship mobility due to the port entry barrier limiting ship speed to less than 5kn. The manoeuvring length and speed analysis for the Port of Venice were straightforward, as ships needed to follow a narrow lane and strict speed limits within the physical barrier to enter the containership terminal within the Venetian lagoon. Cruising and manoeuvring distances were measured along the ship tracks, with speed analysis to detect the activity phase, as presented in Figure 6.6.

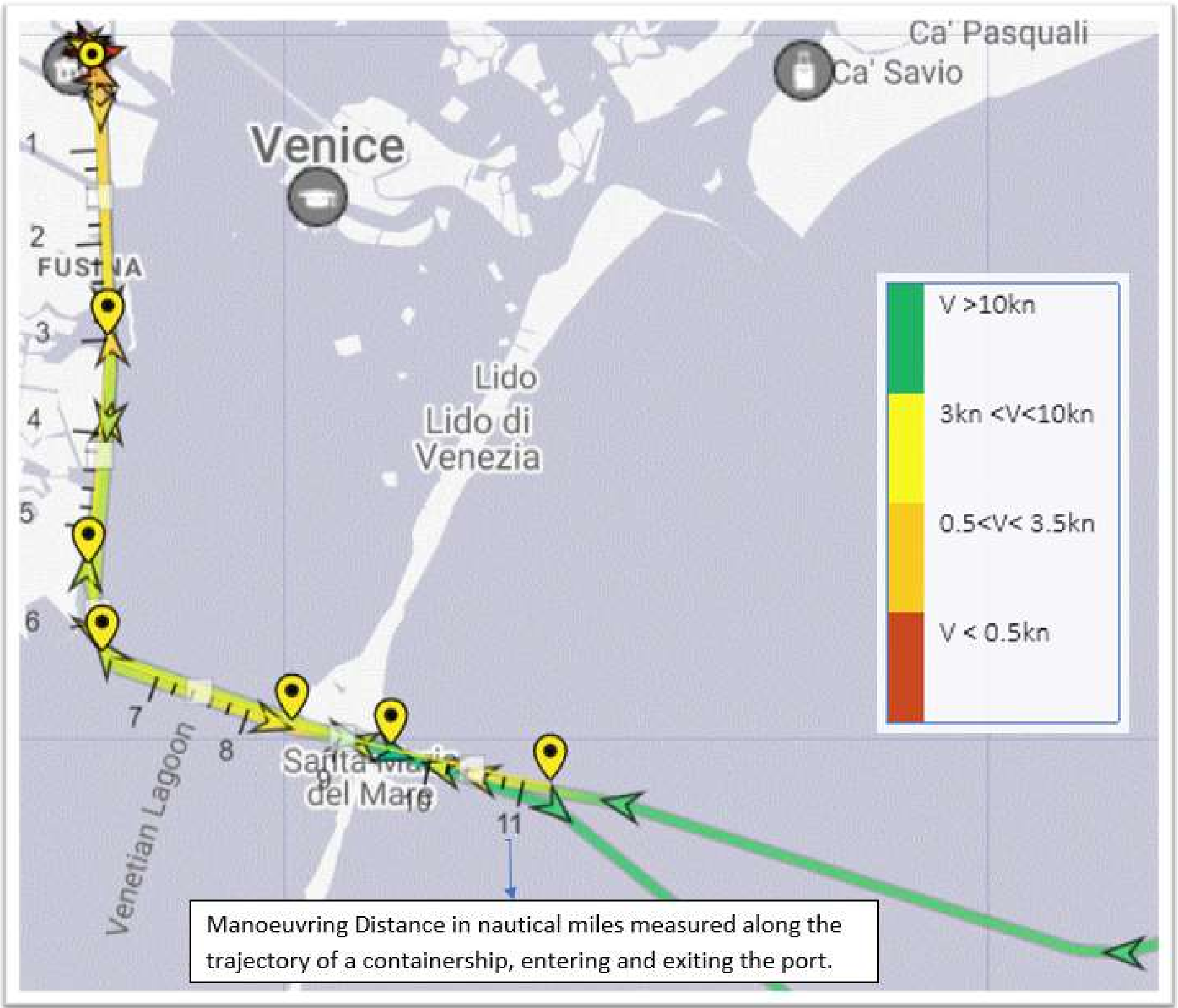

Figure 6.6: Speed and Manoeuvring Distance Analyses for one containership voyage to the Port of Venice

The ship route length was measured along the ship tracks from the berth through the exit/entry of the Santa Maria del Mare channel, up to the 15nm distance from the port. An example of ship route measurement along one past ship track is presented in Figure 6.7.

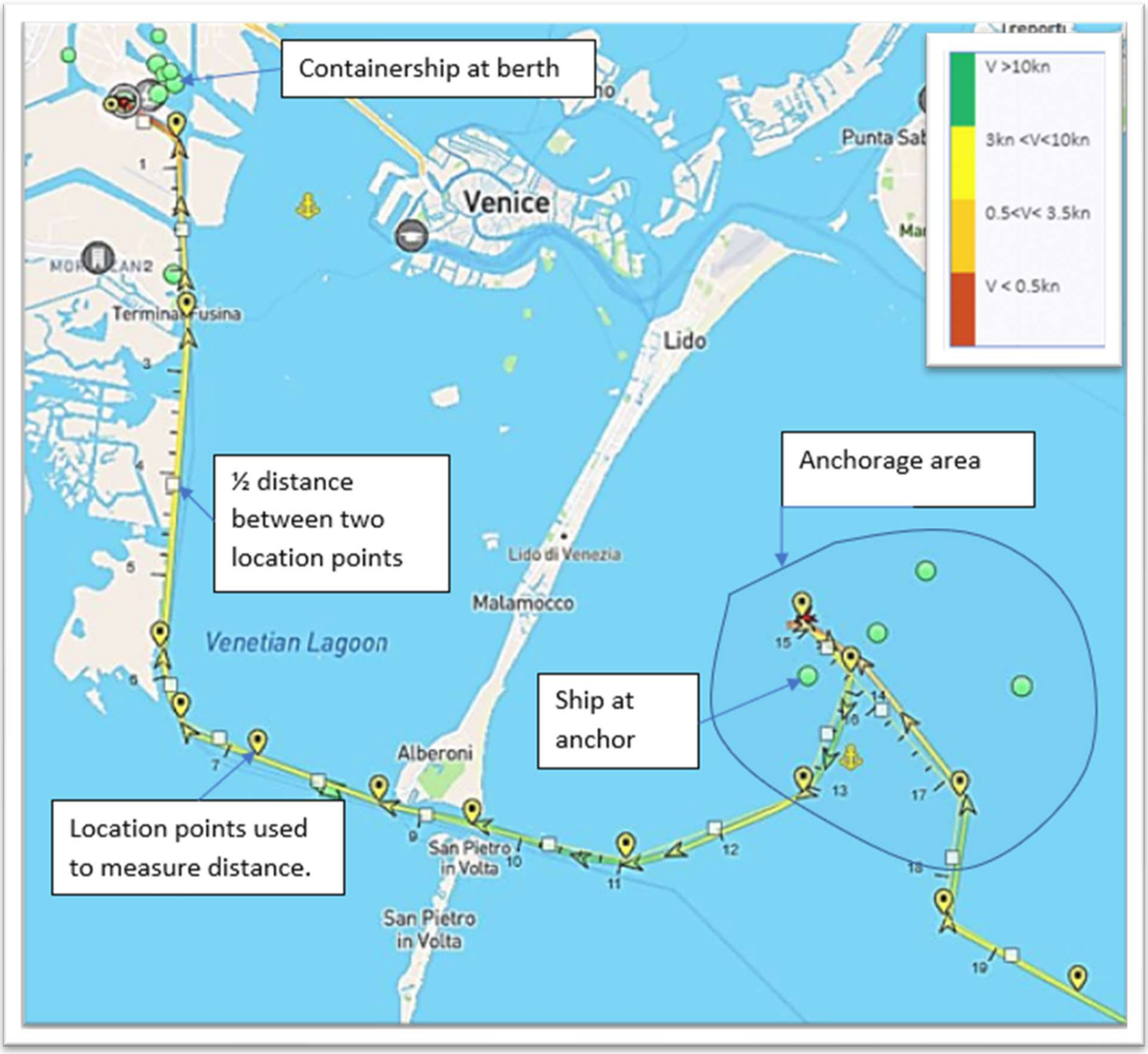

Figure 6.7: Ship track length measurement in nm to establish cruising and manoeuvring distance length

The anchorage to the port was located at a 7 to 10nm radial distance SE of the port near the Santa Maria del Mare channel. Time at the anchorage was retrieved from the calls to the port dataset, followed by the SEA method process, which adds an extra manoeuvring distance to the ships using anchorage.

Ship activity was further analysed along the ship tracks from the Santa Maria del Mare channel entrance to the 90-degree course change area. Ship entry and exit routes and speeds remain equal for the entry and exit route in the described segment.

To conclude, ships entering the port of Venice are on average cruising at 30 to 50% load at the route between the Santa Maria del Mare channel and the port. Ships decelerate/accelerate for 15% of the maintained speed past the point A on the shipping route, presented in Figure 6.8. In the last section to the port along the length of 6nm, ships are at manoeuvring speed.

The average distances needed for input to the SEA method are presented in Table 6 .3.

Table 6. 3: Ship average cruising and manoeuvring distance for input to the SEA methodology for the Port of Venice containership emission estimates

	Average distance in cruising phase [nm]	***Average manoeuvring distance [nm]*** *IF T_{port}>24,* ***(Assumed anchorage distance included)***	***Average manoeuvring distance [nm]*** *IF T_{port}<24* ***(No anchorage)***
Port entry	9.92	6.5	6
Port exit	9.92	6	6
TOTAL	19.84	12.5	12

Figure 6.8: Shortest distance from Ships in Anchorage to the Venice city centre and to the ship berth

6.6. Quantification of Emissions for Containerships in the Port of Trieste

Results of estimates for the Port of Trieste containership emissions are presented in Table 6.4 and Figure 6.9. Result conclusions are discussed further in Section 6.9. and 6.11.

Port of Trieste	***Quantity of Pollutant [tonnes]***	***Pollutant g/TEU***
CO_2 [t]	**7,529.16**	**5.279.26**
SOx [t]	**7.63**	**5.35**
NOx [t]	**127.04**	**89.07**
Total TEU	**1,426,178 TEU**	
Total voyages researched	**380 voyages**	

Table 6. 4: CO_2, SO_X and NO_X emission estimates for the Port of Trieste containership traffic in 2019

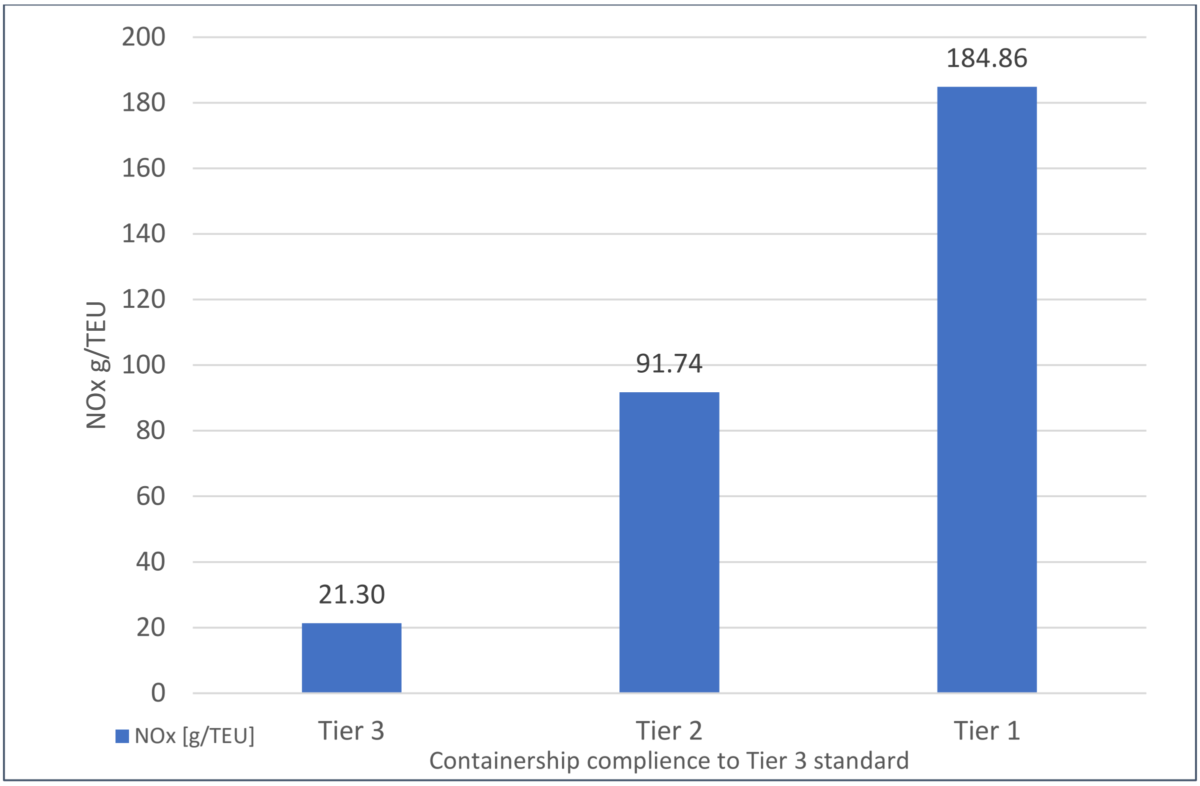

Figure 6.9: Aggregated NO_X emissions for containerships that comply with different Tier in IMO NOx Tier III standard

6.7. Quantification of Emissions for Containerships in the Port of Rijeka

Results of estimates for the Port of Trieste containership emissions are presented in Table 6. 5 and Figure 6.10. Result conclusions are discussed further in Section 6.9. and 6.11

Port of Rijeka	***Quantity of Pollutant [tonnes]***	***Pollutant g/TEU***
CO_2 [t]	**6,705.93**	**5,388.38**
SOx [t]	**5.5**	**4.42**
NOx [t]	**57.6**	**46.28**
Total TEU	**1,244,517 TEU**	
Total voyages researched	**309 voyages**	

Table 6. 5: CO_2, SO_X and NO_X emission estimates for the Port of Rijeka containership traffic in 2019

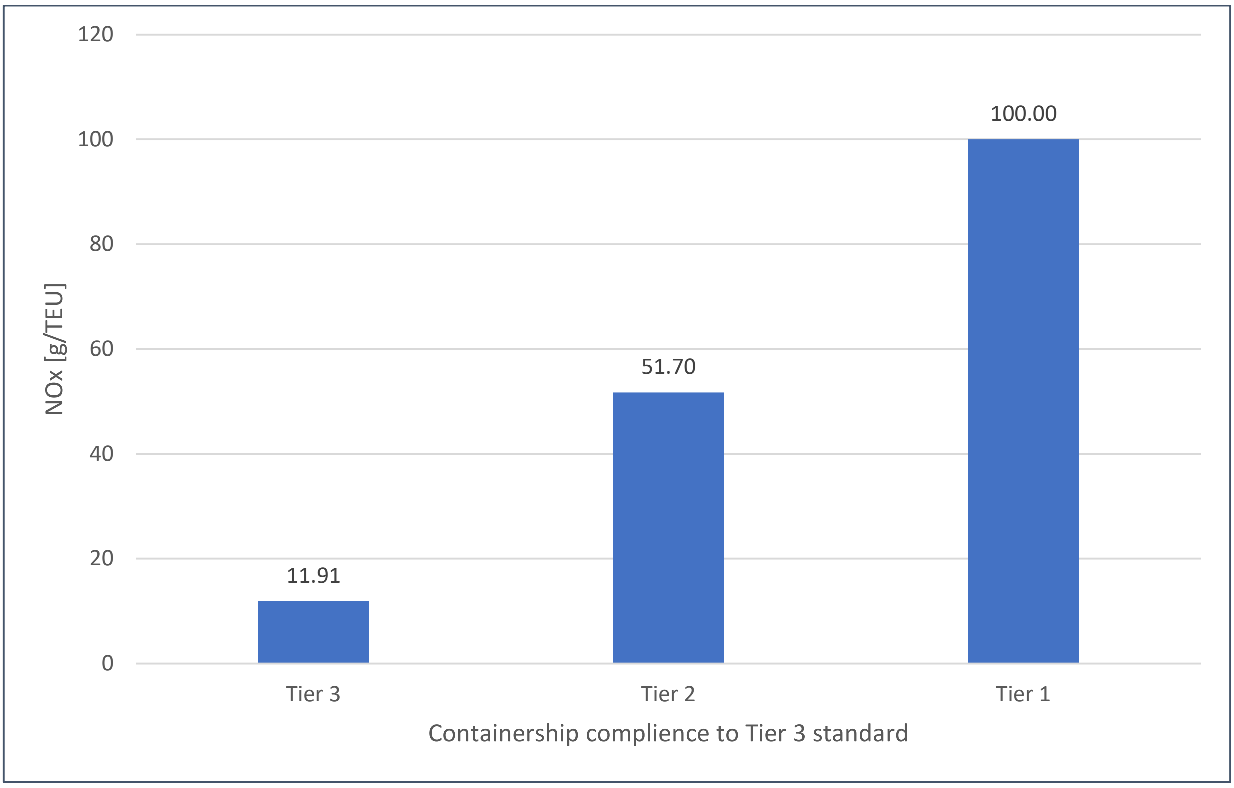

Figure 6.10: Aggregated NO_X emissions for containerships that comply with different Tier in IMO NOx Tier III standard for Port of Rijeka 2019

6.8. Quantification of Emissions for Containerships in the Port of Venice

Results of estimates for the Port of Trieste containership emissions are presented in Table 6.6 and Figure 6.11. Result conclusions are discussed further in Section 6.9. and 6.11.

Port of Venice	*Quantity of Pollutant [tonnes]*	*Pollutant g/TEU*
CO_2 [t]	**15,345.63**	**13,619.07**
SOx [t]	**15.98**	**14.18**
NOx [t]	**395.65**	**351.13**
Total TEU	**1,126,775 TEU**	
Total voyages researched	**664 voyages**	

Table 6. 6: CO_2, SO_X and NO_X emission estimates for the Port of Venice containership traffic in 2019

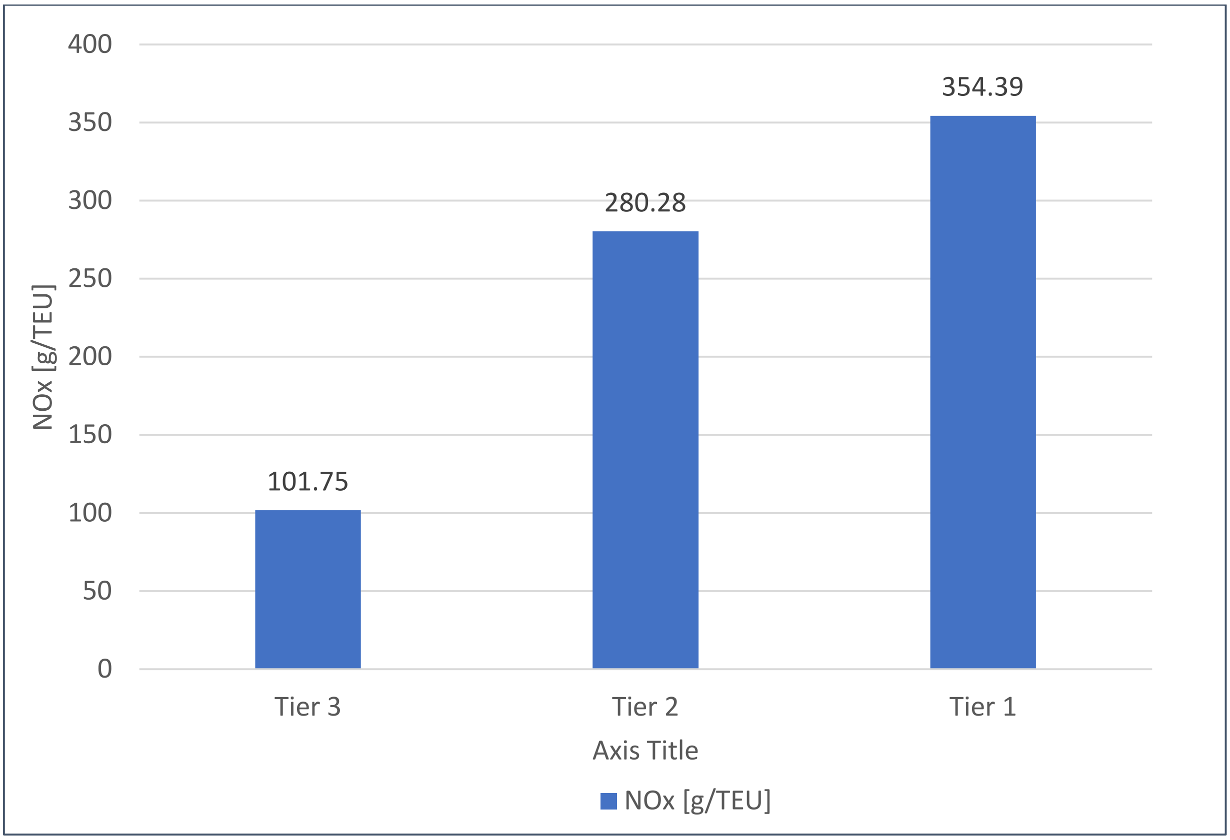

Figure 6.11: Aggregated NO_X emissions for containerships that comply with different Tier in IMO NOx Tier III standard for Port of Venice 2019

6.9. Comparison of emissions in ports

The SEA method enables the estimation of emissions from ships, and it can be used to compare the efficiency of reduction measures in ports. Three case study ports, Rijeka, Trieste and Venice, were compared for different factors that impact the quantity of emissions to demonstrate the SEA method applicability.

The three ports were first compared for emissions of pollutants CO_2 and SO_X expressed in grams per containership carried, as presented in Figures 6.13 and 6.14. The difference in CO_2 and SO_X emissions was related to the difference in ship capacity and size, which creates higher emissions for the same throughput for smaller ships that need to make several voyages for the same capacity that large ships achieve in a single voyage. Ship sizes were compared for the three ports in the graph in Figure 6.15. The graph shows that the port of Venice had the highest number of ship voyages because of its limited access through the barrier to the port and lack of berth access and capacity for large containerships. Port access limitations, analysed previously in Section 6.5., explain the need for small containerships and the reason for significantly higher emissions of CO_2 and SO_X compared to the other two ports. The Ports of Rijeka and Trieste both have natural sea bays allowing large capacity containerships, resulting in higher efficiency and lower emissions.

The three ports have similar throughput of containership capacity of between 1.2 to 1.4 million TEU per year, measured in maximal ship capacity.

The number of containerships complying with IMO Tier III standards for NO_X was presented in Figure 6.16 and can be related to Figure 6.13, which presents the relative amount of NO_X emissions in grams per TEU. A strong correlation can be observed between the amount of NOx emissions and the percentage of Tier 1 and Tier 2 ships.

Results show that the port of Venice has the highest relative NOx emissions [g/TEU]. As the size of ships calling to the port of Venice is limited to less than 7000 TEU, a high number of ships is needed; however, the fleet of that size is older than 2016 and belongs to Tier 1 and Tier 2 emission standards, which contributes up to 80% more emissions than new ships that comply to Tier 3 standards.

Ports of Rijeka and Trieste have access to the port for ships of more extensive scale and capacity, which results in lower emissions. Additionally, containerships are growing in size, meaning larger ships are newer and more likely to comply with stricter Tier 3 regulations. Both ports, Trieste and Rijeka, have more containerships calling that were built after 2016 and comply with strict Tier 3 standards.

The SEA method enables accurate identification of ships' Tier standards and assuming ships' compliance; it provides a tool to estimate emissions quantities under current and future regulations and traffic management rules. The SEA method provides a tool for policymakers and port management to frequently inspect the impact of rapid changes in the condition of ship technical measures on the emission quantities.

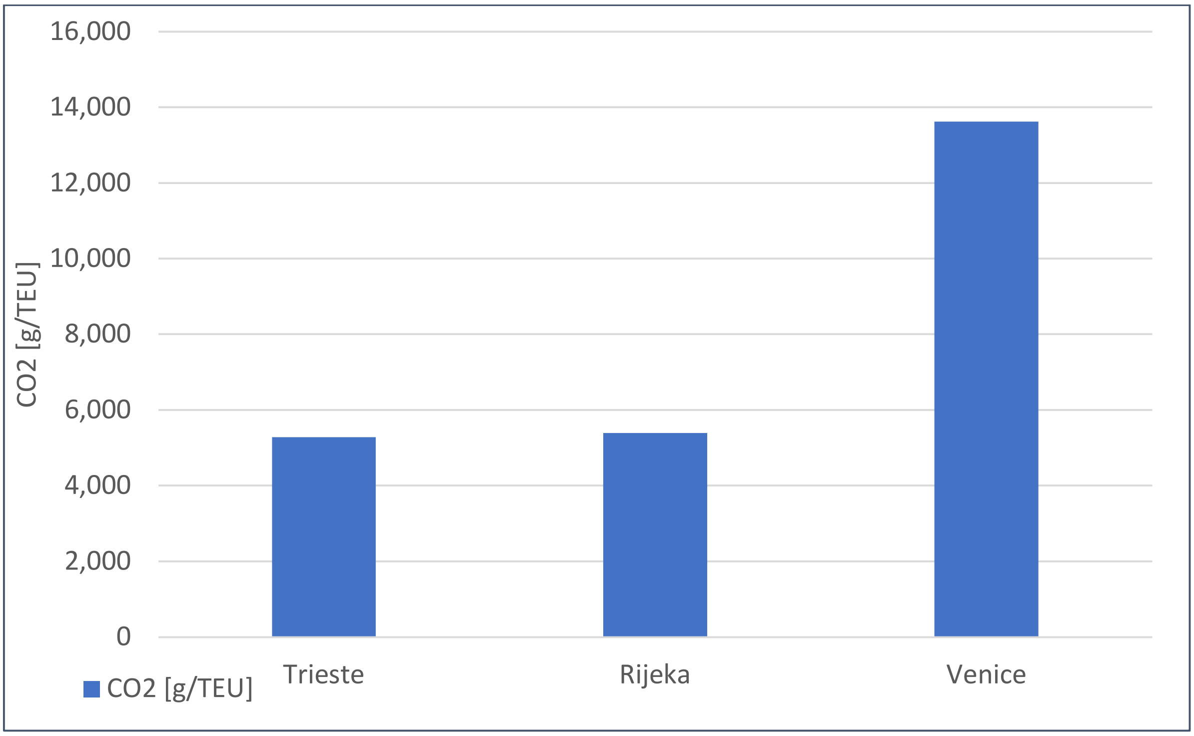

Figure 6.12: Comparison of CO_2 emissions for containerships in ports of Trieste, Rijeka and Venice in 2019

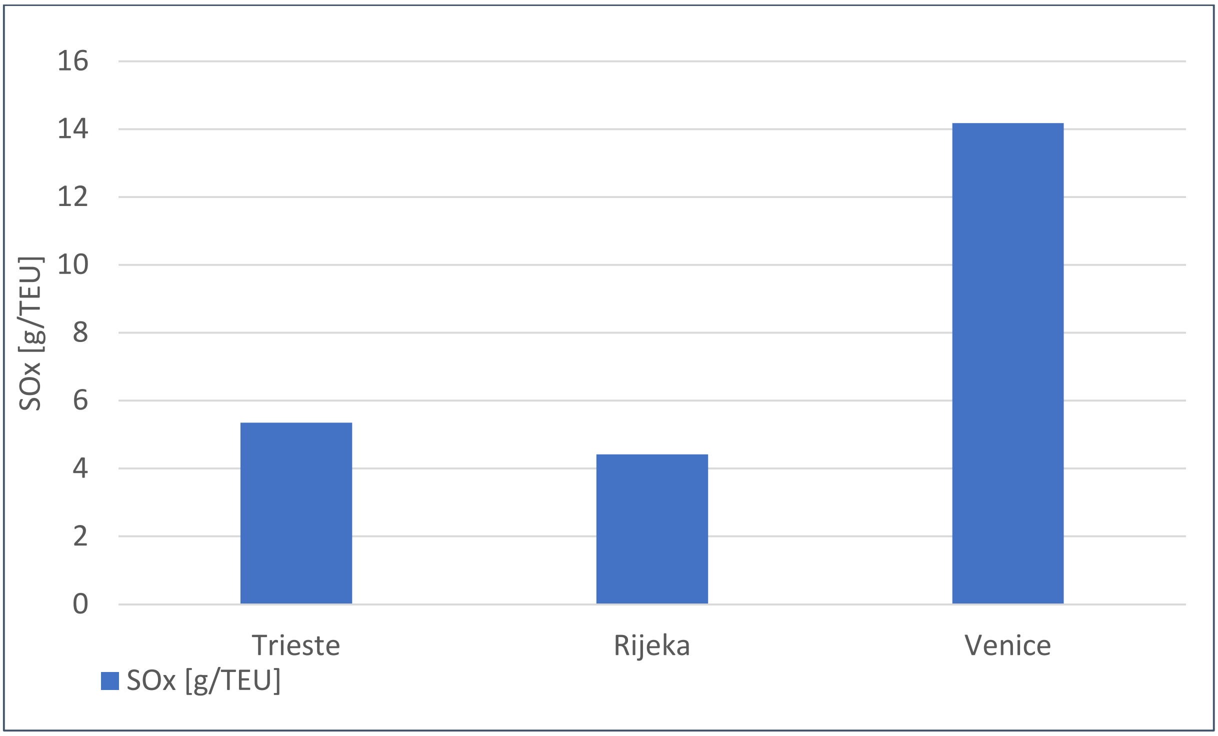

Figure 6.13: Comparison of SO_X emissions for containerships in ports of Trieste, Rijeka and Venice in 2019

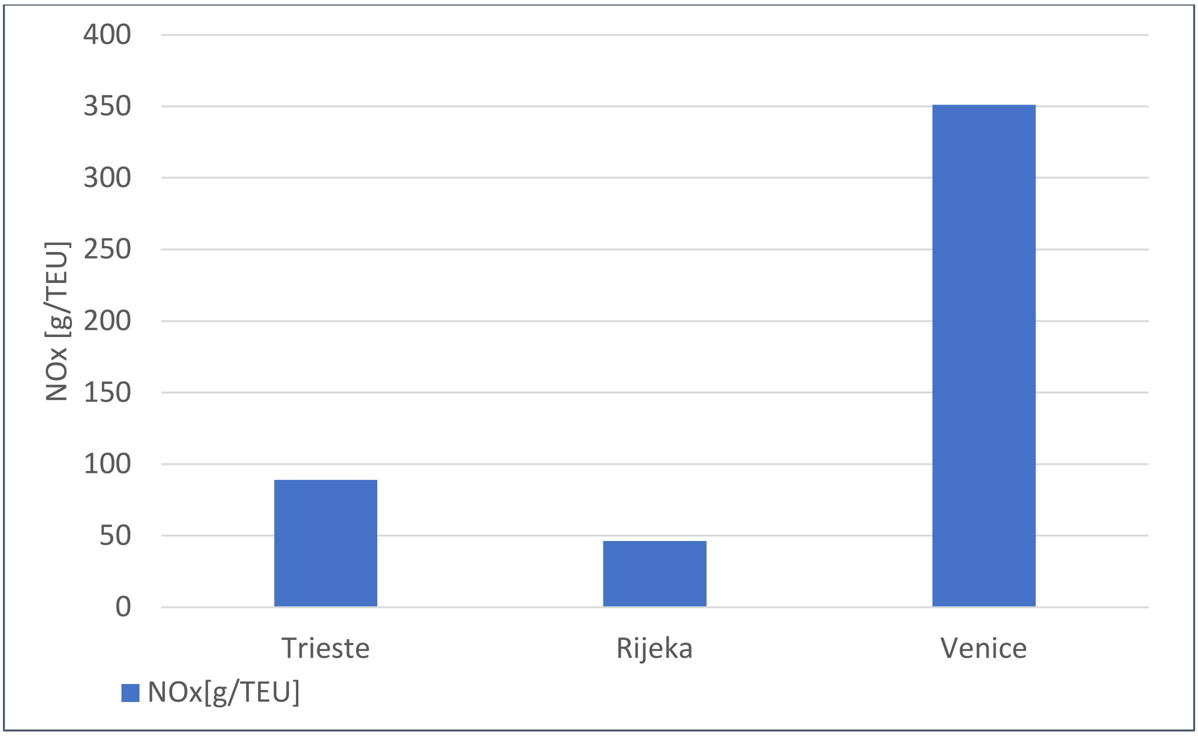

Figure 6.14: Comparison of NO_X emissions for containerships in ports of Trieste, Rijeka and Venice in 2019

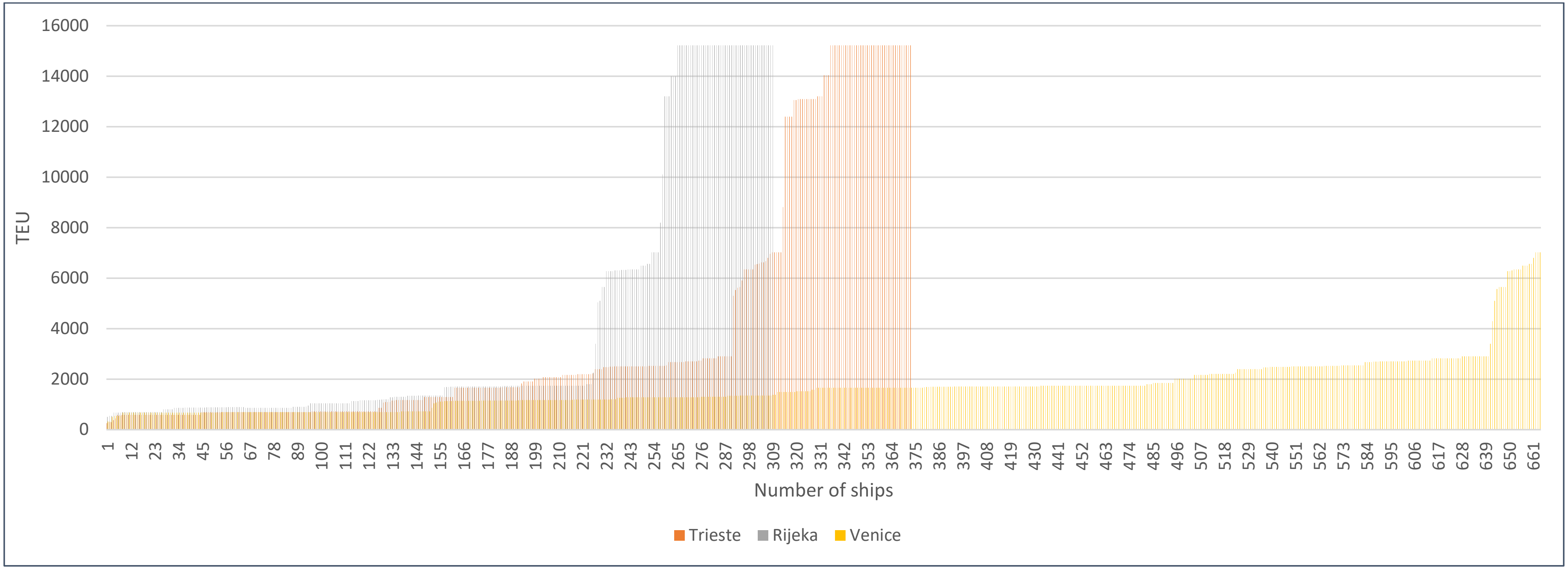

Figure 6.15: Comparison of the number of voyages to the ports and maximum capacity of ships calling to the ports of Trieste, Rijeka and Venice 2019, with an overall yearly capacity of between 1.2 to 1.4 million TEU

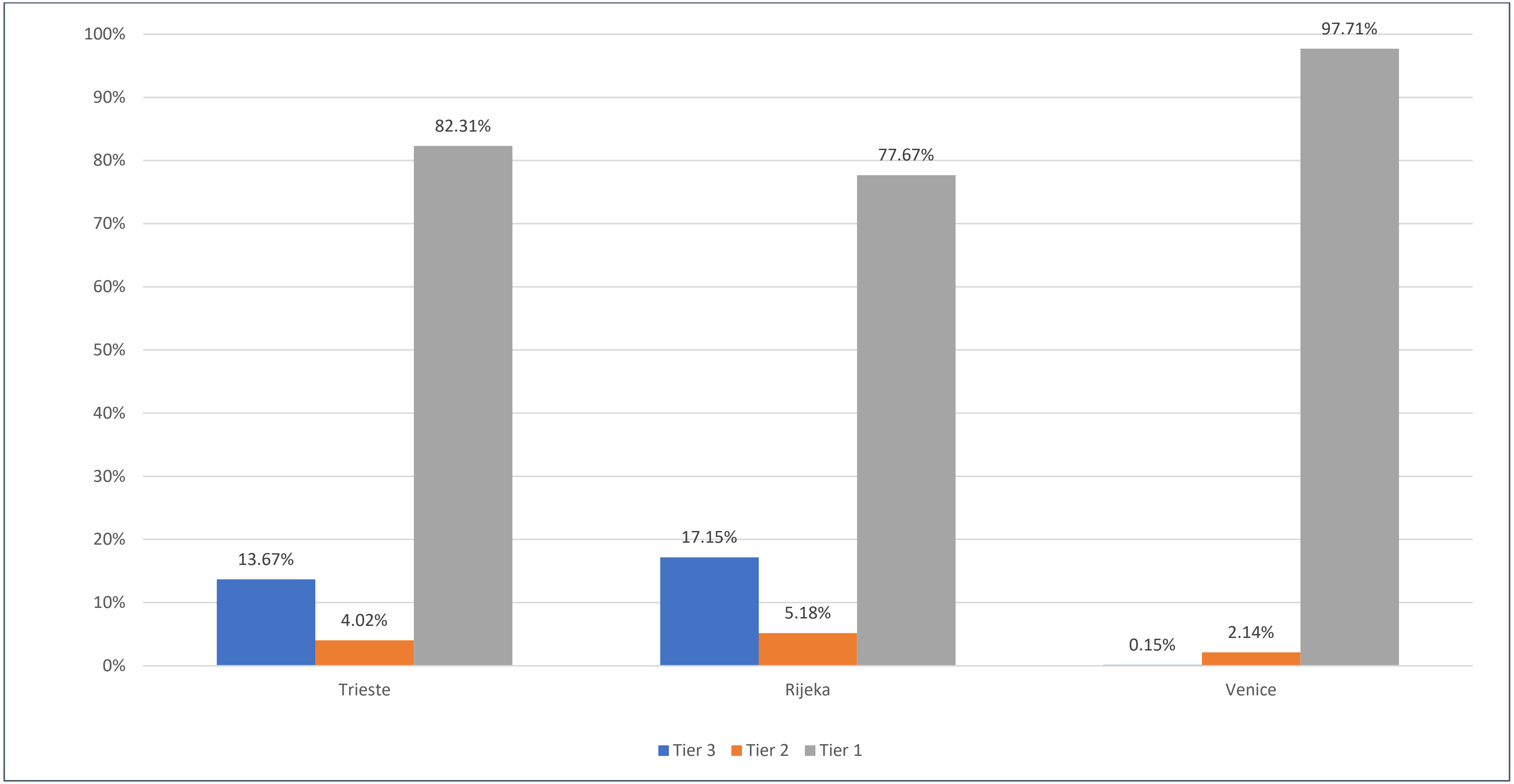

Figure 6.16: Comparison of the number of ships in compliance with IMO Tier III standards in 3 ports

6.10. Analysis of Ship Emission Reduction Measure Effectiveness

The SEA method presents a tool for assessing ship emissions; however, it can also be applied in forecasting to understand the effectiveness of future regulations before those regulations are put into action. This was demonstrated in the example of the actual data for the Port of Venice containership voyages. The case study for the port of Venice was selected for the study in emission reduction measure effectiveness because it generates significantly higher amounts of CO_2, SO_X and NO_X emissions compared to the other two researched ports.

The SEA method was applied in Section 6.8 to estimate ship exhaust emissions for the Port of Venice. The same data sample is now used to forecast possible case scenarios to analyse each scenario's effectiveness in reducing emissions in the Port of Venice.

The following scenarios were tested to analyse the possible reduction of emissions:

A) Ship time in port was first reduced by 10% in the cruising phase under the following conditions: ships continue to cruise at the same slow steaming speed, but the route where ships approach the port is reduced by 10%.

B) Additional reduction is introduced by shortening the time that ships spend in berth (port operations) by 10%.

Reduction in emissions by scenarios A and B are presented in Table 6.7.

Port of Venice	*Quantity of Pollutant [tonnes]*	*A) Quantity of Pollutant [tonnes] for 10% reduced time cruising*	*Reduction in emissions achieved by Scenario 1a*	*B) Quantity of Pollutant [tonnes] for a reduced time at berth for 10%*	*TOTAL REDUCTION of EMISSIONS [tonnes of pollutant]*	*The total reduction in emissions achieved by Scenario A and B combined*
CO_2 [t]	**15,345.63**	**15,162.16**	**1.2 %**	**14,516.20**	**829.43**	**5.4%**
SOx [t]	**15.98**	**15.78**	**1.25%**	**15.11**	**0.87**	**5.5%**
NOx [t]	**395.65**	**390.98**	**1.18%**	**374.29**	**21.36**	**5.4%**
Total TEU	**1,126,775 TEU**					
Total voyages researched	**664 voyages**					

Table 6. 7: Scenario A: Reduction in emissions if the length of cruising route is optimised and Scenario B: Reduction in emissions if time at berth is reduced by 10%

6.11. Conclusions of comparison of the ports results

The SEA methodology was applied to estimate emissions in three ports in the Adriatic Sea ports of Trieste, Rijeka and Venice. All three ports are located close to or within their port cities, bearing the same name as the ports. Those densely populated port-city areas need to yearly assess and report ships' emissions according to EU regulations; hence regular ship emissions assessment is needed. Currently, this reporting is not publically available, and the SEA method is demonstrated to enable the practical tool for ship emission assessments. A transparent ship emission reporting is necessary to understand the quantity of ship-generated concentrations of CO_2, SO_X and NO_X near cities and their possible impact on air quality, river and seawater quality.

The SEA method results present emissions for all three ports in grams of CO_2, $SO_{X,}$ and NO_X emitted per containership TEU. This way of emission quantification enables the comparison of the effectiveness of regulating emissions within the port boundary, regardless of port size. Ports of similar throughput were selected, enabling a comparison of organisational features.

The port comparison results show the exact percentage of Tier1, Tier2 and Tier 3 compliant ships, which helps to understand the rate at which new emission optimised ships replace old and obsolete high emitting Tier 1 and Tier 2 ships. Evidence is provided that shows the quantity of emissions for three groups of ships, complying with different Tier regulatory levels, I, II and III. Ports with the lowest NOx emissions, Rijeka and Trieste, also have the lowest number of ships calling to the port while maintaining a similar throughput of 1.2 million TEU. Lower overall emissions of NOx were achieved because Tier 3 ships emit 80% less NOx and because Tier 3 ships are newer than Tier 1 and 2, with lower emission rates per volume of cargo carried. The SEA methodology was applied to test further the understanding of the quantity of emissions of NOx that could be reduced with the NECA emission reduction measure. Scenarios were tested in the next section to estimate the reduction in NOx in all three ports, if NECA regulations were imposed.

While the transition to Tier 3 standard compliance (technical emission reduction measure) is expected to happen gradually, it is vital to explore management and policy emission reduction measures to reduce emissions near the coastlines and while ships are in ports. The SEA methodology provides a tool to estimate current emissions from ships and regularly evaluate increases in Tier 3 compliant ship technical measures.

Results show that if the reduction measures of combined scenarios A and B are applied, total emissions will reduce by 5.4 to 5.5%. Scenario A could be put into practice by limiting the milage ships cross within the ship anchorage (Figure 6.7 and 6.8) by 10%. This organisational effort could reduce 183 tonnes of CO_2, 200kg of SO_X and 4,7 tonnes of NOx per year, which are emitted less than 5 nautical miles from the centre of the historic City of Venice, which can be seen in Figure 6.8.

This example demonstrates the capability of the SEA method for emission forecasting, which can support decision making bodies in analysing the effectiveness of potential emission reduction measures.

The SEA method enables practical testing of reduction measures that include reduction of shipping route lengths, average ship speeds and time at anchorage, to estimate the reduction in emissions that could be achieved with those measures. The SEA method provides a practicable tool that uses widely accessible resources and hence enables rapid processing to provide results for regular weekly or monthly emission inventories.

6.12 Analysis of Effectiveness of NECA in ports of Rijeka, Trieste and Venice

Three case study ports were assessed for emission reductions of NOx, which could be achieved in the event if NOx Emissions Control Area is declared for the Adriatic Sea.

The SEA methodology was applied under the assumption that all three ports keep the same throughput and same ships in size, volume and schedule. Existing ships for 2019-2020 traffic were assessed with the NOx regulatory emission levels increased to Tier 3, and results are presented in Tables 6.8, 6.9 and 6.10.

Port of Rijeka	*Quantity of Pollutant [tonnes/year]*	*Pollutant g/TEU*
NOx current	**57.6**	**46.28**
NOx NECA	**18.32**	**14.7**
Reduction in Emissions by NECA regulation	**39.28**	
Total voyages, TEU researched	**309 voyages**	**1,244,517 TEU**

Table 6. 8: Reduction in NO_X emissions in case of NECA compared to current emissions for the port of Rijeka

Port of Venice	*Quantity of Pollutant [tonnes/year]*	*Pollutant g/TEU*
NOx current	**395.65**	**351.13**
NOx NECA	**76.57**	**67.96**
Reduction in Emissions by NECA regulation	**319.08**	
Total voyages, TEU researched	**664 voyages**	**1,126,775 TEU**

Table 6. 9: Reduction in NO_X emissions in case of NECA compared to current emissions for the port of Venice

Port of Trieste	*Quantity of Pollutant [tonnes/year]*	*Pollutant g/TEU*
NOx current	**127.04**	**89.07**
NOx NECA	**38.27**	**26.83**
Reduction in Emissions by NECA regulation [t/year]	**88.77**	
Total voyages, TEU researched	**380 voyages**	**1,426,178 TEU**

Table 6. 10: Reduction in NO_X emissions in case of NECA compared to current emissions for the port of Trieste

If NECA is declared in the Port of Rijeka area, ships will emit 68.2% less NO_X or 39.28 tonnes of NOx/year. The reduction of emissions in the port of Venice would be 81% which is significantly higher with reduced 319.08 NOx tonnes per year. In the port of Trieste, NECA regulation would stipulate a reduction of 70% of yearly NO_X emissions from ships, or 88.77 tonnes of NO_X.

In the event that NOx Emission Protected Area is agreed upon amongst the countries sharing the coastlines of the Adriatic Sea, more than 447.13 tonnes (total NOx reduction of the three largest containership ports) of noxious gases could be reduced within 20nm from the ports of Venice, Trieste and Rijeka. However, this reduction would impact the whole Adriatic Sea basin, which containerships need to cross to get to ports of destination in the north. If emission reduction in the port boundary area is scaled to the Adriatic Sea containership routes, a reduction of NOx of between 60 to 80% would be achieved in the entire region, even if NECA is declared only in the North of the Adriatic Sea.

6.13. Summary of Chapter 6

The SEA methodology was applied in three ports, Trieste, Rijeka and Venice, to estimate CO_2, SO_X and NO_X emissions generated by containerships and to understand reduction measure efficiency. The SEA methodology was further applied to assess emissions and forecast efficiency in scenarios of different regulatory measures. A reduction in emissions of pollutants was estimated for the event of the implementation of NECA in all three ports. Results showed that 447.13 tonnes of NOx could be reduced each year in the North Adriatic Sea area around the ports of Rijeka, Trieste and Venice in the event that NECA regulations are stipulated. This would contribute to an additional reduction of NOx emissions, between 68 and 81%, along the containership shipping lanes through the Adriatic Sea.

The quantities of CO_2, SO_X and NO_X were presented for the case study ports as grams of pollutants per volume of containership cargo in TEU. This allowed the comparison of ports' emission reduction effectiveness.

The results showed significant differences in quantities of NOx in the port of Venice, where values were higher than in the other two ports. A comparison of ship compliance to the IMO NOx standard showed the relation of standard containership compliance to total NOx emissions quantities. Additionally, results showed that the higher number of ship voyages needed to transport similar throughput in Venice impacts emission levels. This is why the port of Venice, which cannot be accessed by newer and larger ships, has higher NOx and overall emissions levels, as older ships do not comply with stricter Tier III standards. Additional research was conducted to analyse the effectiveness of two scenarios intended to reduce emissions in the port of Venice.

The SEA method was used to analyse two emission reduction scenarios applied to the case study of containerships in the Port of Venice, which was estimated to have the highest overall and relative emissions of the three researched ports.

The SEA method was applied to estimate the possible reduction in emissions in the highest polluting port if waiting time in port is reduced by 10% and the cruising route within the anchorage is reduced by 10%. The SEA method results showed that 5.4 to 5.5% overall emission reduction would be achieved by a 10% reduction in time and increase in route effectiveness, which would, in the case of the port of Venice, reduce 2O tonnes of SOx emissions per year, 829 tonnes of CO_2 and 21 tonnes of NO_X yearly, within 5 nautical miles of the centre of the city.

Chapter 7. Conclusion

Ships using fossil fuels emit greenhouse gases and toxic nitrous and sulphur oxides, and quantities of those exhaust gasses need to be estimated. Existing methodologies for estimation of ship exhaust emissions use either a rapid top-down approach, which provides rough estimates based on fuel sale statistics; or a bottom-up approach which is accurate; however, it requires detailed information on ship voyage circumstances, speed, external factors and technical data, which is time-consuming and expensive. The research was conducted to develop a methodology that will enable practical, time and data-efficient assessment of emissions from ships in different areas globally, to quantify emissions of CO_2, SO_X and NO_X and present evidence of ship emission footprint, which can be used to understand regulation effectiveness, plan or improve policy and managerial measures. The methodology needed to be inclusive of diverse changes in regulations and technology and enable quantification of ship emissions for any port and geographic location using readily available and inexpensive data.

The research question answered by this Thesis was: ***How to rapidly estimate emissions from ships in defined geographic areas to enable assessment of regulation effectiveness by using publically available resources?***

The methodology was developed, which combines top-down and bottom-up approaches in ship emission estimation, achieving data and time effectiveness in the quantification of CO_2, SO_X and NO_X emissions for ships in designated areas. The Ship Emissions Assessment (SEA) methodology utilises previously unused datasets, which were identified to avoid the need and costs of massive AIS historical datasets. The SEA methodology estimates emissions from ships rapidly but accurately with comparable results to bottom-up methodology estimates. The SEA method enables modelling of emissions with consideration of the vessel-based technical emission reduction measures to assess the percentage of ships that comply with the strictest IMO Tier III NO_X regulations and the impact of emissions from ships complying with Tier 1 or Tier 2 NO_X regulatory measures. Additionally, the SEA methodology quantifies CO_2 and SO_X emissions to understand if existing regulations reduce emissions effectively and rapidly enough to mitigate the increase in ships number and trade intensity. The case study was conducted on containerships in the North Adriatic Sea in three ports Rijeka, Trieste and Venice.

7.1 Novelty of the Work and Contributions

This Thesis presents the Ship Emissions Assessment (SEA) methodology, which provides a tool to assess emissions from ships in conditions where other models are inadequate because of time-consuming operations and data acquisition complexity.

A method that is practicable, as quick as top-down methodologies but accurate as bottom-up methods, is required to assess ship emissions in regional seas, coastal waters and ports. The SEA methodology provides a practicable tool to assess emissions from ships accurately and regularly (weekly, monthly and yearly) in designated areas, including ports and coastal waters. The SEA method can be applied to assess emissions for reporting purposes, to assess at what rate ship technical measures impact CO_2, SO_X and NO_X emission levels. Additionally, the SEA methodology can assess the effectiveness of regulations and policy measures and how they impact ship emission quantities. The SEA methodology uses publicly available datasets, which can be accessed globally to enable a wide range of stakeholders with a practicable emission estimation tool**.**

The SEA methodology compromises the bottom-up, detailed technical vessel-based data and top-down rapid average values for ship activity and voyage information. The novel SEA method covers the gap between the two extreme ends of the accuracy results scale, the top-down and the bottom-up. The SEA method is designed to deliver results at the accuracy level as defined by the IMO (2018 GEF-UNDP-IMO GloMEEP Project and IAPH, 2018), which is needed by policymakers and regulatory bodies and to report emissions or plan future regulations.

The SEA method is an innovative hybrid solution that enables 10 to 100 times quicker dataset acquisition and processing time compared to the bottom-up methodology, Chapter 5, Section 5.7. Additionally, the SEA method reduces data requirements 50 to 500 times, saving historical data purchasing costs, as presented in Section 5.7., Tables 5.4 and 5.5.

Research results demonstrate that the SEA methodology can be used in different ports and geographical areas to estimate exhaust emissions from shipping with sufficient accuracy to understand the reduction of emission effectiveness and plan further measures to optimise energy demand and reduce emissions.

The SEA methodology can be used to quantify emissions of CO_2, SO_X and NO_X relative to the volume of transported cargo or passengers (for containerships in TEU) to compare the efficiency of ports and port emissions reduction management; or to compare reduction measures planning and development proposals, to forecast efficiency of new regulations.

The SEA method provides novelty by solving the identified gaps in the existing methods:

1) ***It quantifies emissions considering ship technical measures and the impact of ship NOx standard compliance to emission reduction in the designated area. This is important for providing the evidence to policymakers and countries applying for new NECA areas.***
2) ***It provides a hybrid between the top-down and bottom-up emissions estimation methodologies that reduce the complexity of processing, size and cost of datasets for ship emission estimation***
3) ***It provides a tool to assess emissions rapidly but precisely, using previously not used data and reduces the time for data acquisition and processing***
4) ***It provides the tool for spatial emissions presentation for any port globally, enables reporting of emissions from ships in geographic areas, and identifies critical emission areas in coastal waters.***
5) ***The SEA methodology provides a tool for planning and forecasting the new emission reduction regulatory measures and shows the effectiveness of measures before their application***
6) ***The SEA methodology enables the estimation of ship energy demand, which can be applied in planning alternative propulsion systems, shore-side electricity needs, or strategic shipping energy efficiency plans.***

The novel SEA methodology provides an alternative to massive AIS datasets processing to obtain ship activity data and estimate ship energy demand, with the ability to process 1200 ship voyages in less than 12 hours in the conditions where one person is using a standard laptop (i5 processor). The SEA uses readymade sets of previously unused voyage data combined with processed aggregated one-year maps of global ship tracks. The SEA methodology enables the presentation of aggregated ship emissions generated by ship exhaust on the spatial map of historic ship tracks.

To conclude, if aggregated results are required to estimate emissions in ports, regional or global coastal waters, the current complex and resource-demanding, bottom-up and vessel-based estimates now have a more straightforward, inexpensive and less computationally demanding alternative in the form of the novel SEA method.

7.2 General Conclusion

The SEA methodology simplifies the otherwise time-consuming process of AIS data acquisition. Using available one-year ship tracks maps and thus bridging this costly process of data acquisition, the SEA methodology successfully provides comparable results for aggregated emissions of up to one year of traffic for the designated geographic area and selected ship type. This part of the novel SEA methodology can be classed as a top-down approach. However, the SEA methodology is further combining parameters of the top-down with a bottom-up approach in an innovative way to optimise vessel-based emission estimation.

The SEA methodology can be applied to compare ports for the effectiveness of emissions policy and regulations, which was explored by comparing three ports in the Adriatic Sea, Port of Rijeka, Port of Trieste and Port of Venice. Emissions of CO_2, SO_X and NO_X, were quantified for one year of containership traffic in each port. Spatial presentation of results was demonstrated for the Trieste Bay area for CO_2 in section 6.3.

Vessels were assessed for speed and activity in port boundary areas, which has resulted in emission quantification and spatial presentation. The results presented can be used to assess and compare the port's emission measures efficiency, using the mass of pollutant per volume of cargo for the comparison unit. Results presented in chapter 6 demonstrated that ports with the least manoeuvring time, port processing time, and lower ship speeds have the least emissions. Parameters that had the highest impact on overall emissions were the age of ship fleet that reflects ship sizes, total engine power, and Tier standard compliance, which consequentially affects emission factors.

Additionally, the SEA methodology was applied to quantify NO_X emissions in the event that NECA regulatory measure is enforced in the North Adriatic Sea. The reduction in emissions for this case scenario varies from 68.2% for the port of Rijeka, 70% for the Port of Trieste and 81% for the port of Venice, which is in total a reduction of 447.13 tonnes of NO_X per year.

The SEA methodology can estimate ship energy demand in ports, emissions quantity and spatial distribution, providing evidence in feasibility studies towards clean energy in ports and shore-side electricity for ships in berth operations.

The SEA methodology for ship emission assessment applies to all regional seas and ports, requiring less data resources than existing methods, and rapidly yet accurately enables understanding of the effect of ship emission reduction measures. It is a practicable tool that can run on a conventional computer without specialised equipment. Therefore, the SEA methodology can be applied on a standard laptop with an i5 processor and internet access, enabling most stakeholders in the shipping industry to assess ship emissions in their coastal waters.

7.3 Recommendations for future work

The SEA methodology was applied to assess emissions in three ports of the North Adriatic Sea. The case study area can be further expanded, and estimates provided to quantify emissions from containership traffic for the whole of the Adriatic Sea. This can be obtained by extending the port boundary from the current 20nm to the entire length of the shipping lanes from the Strait of Otranto to each port along the Adriatic Sea coastlines, with the addition of containership traffic calling to the other Adriatic Sea ports.

The SEA methodology can further be adjusted to estimate other merchant ship types and different types of fuel or propulsion. For example, applying fuel cell technology for power generation on ships for hoteling reduces NOx emissions entirely. However, CO_2 emissions still need to be accounted for. The SEA methodology can be used to forecast CO_2 emission for the fleet of ships using the fuel cells for hoteling in ports and compare it to current fleet emissions for a different type of ships which apply this technology, like cruise ships. Application of the SEA to other types of power generation systems or fuels requires the usage of appropriate emission factors, which can be obtained from system manufacturers.

The SEA methodology could further be applied in different areas globally to assess emissions and provide evidence of the quantity of reduced emissions in case of implementing different emissions reduction measures.

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